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THESIS

AN ANALYSIS OF GPS NAVIGATION SOLUTIONS FOR SHUTTLE MISSION STS-69

by

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September 1996

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13. ABSTRACT *(maximum 200 words)*

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GPS receiver navigation solution data from Shuttle mission STS-69 was made available by NASA and provided an opportunity for evaluating GPS performance in low Earth orbit. NASA ground tracking network and Tracking and Data Relay Satellite (TDRS) data for this mission provided a reference for comparison. Analysis of the data was accomplished using Satellite Tool Kit (STK) for visualization and Matlab routines for data comparison.

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AN ANALYSIS OF GPS NAVIGATION SOLUTIONS FOR SHUTTLE MISSION STS-69

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ABSTRACT

The NAVSTAR Global Positioning System (GPS) has provided a quantum leap in real-time autonomous navigation capabilities. NASA's Space Shuttle will be receiving an integrated GPS capability in the near future, and the orbiter Endeavour has been equipped with a stand-alone GPS receiver. Although much data is available regarding spacecraft GPS receiver performance at higher altitudes, little information is available for spacecraft at Shuttle altitudes of approximately 400 km where drag and gravity effects are more pronounced.

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I. INTRODUCTION

The NAVSTAR Global Positioning System (GPS) has provided a quantum leap in real-time autonomous navigation capabilities. GPS technology has been applied in numerous fields and has now become a method for autonomous spacecraft navigation. Flight experience with the Topex/Poseidon spacecraft has indicated that very precise spacecraft orbit information can be obtained based on GPS measurements. NASA's Space Shuttle will be receiving an integrated GPS capability in the near future, and the shuttle Endeavour has been equipped with an operational stand-alone system. Although much data is available regarding spacecraft GPS receiver performance at higher altitudes, little information is available for spacecraft at Shuttle altitudes of approximately 400 km where drag and gravity effects are more pronounced.

GPS receiver navigation solution data from Shuttle mission STS-69 has been made available by NASA and provides an opportunity for evaluating GPS performance in low earth orbit. NASA ground tracking network and Tracking and Data Relay Satellite (TDRS) data for this mission was also available for comparison. The objective of this thesis was to compare Shuttle GPS receiver navigation solutions with the NASA reference track. Data comparison routines written in Matlab were used to analyze both sets of state vectors. The visualization features of the orbit analysis software package Satellite Tool Kit (STK) aided the analysis of the data sets.

A. GPS BASICS

1. System Operation

GPS was developed by the Department of Defense (DoD) as a worldwide satellite-based radionavigation system which provides users with position, velocity and time information. Using the concept of ranging, the system measures the distance to several satellites to determine position. Ranging is dependent on time synchronicity among the receiver clock and the satellites. The satellites transmit radio pulses in the form of distinct

pseudo-random sequences at specific known times. The receiving equipment recognizes these sequences and measures the precise time at which the pulses arrive. Based on the transmission and reception times, the time it took the pulses to travel from the satellite to the receiver can be determined. Since the speed of light is constant and the travel time of the pulses is now known, the range to the satellite can be calculated.

Determining the range to a particular satellite places the user on a sphere with a radius equal to this range. The intersection of two spheres of position is a circle, and the intersection of three spheres is two points. Position can be determined using three satellite ranges because the ambiguity of the second point can usually be resolved as an unreasonable solution. The intersection of four spheres of position produces a single point. (Herring, 1996, p. 46)

Ranging requires that the receiver's clock be synchronized with the satellite's clock; however, in order to support receivers with less than perfect chronometers, it is necessary to apply correction and this requires a fourth satellite as shown in Figure 1.1. First, ranges to the four satellites are calculated using the original receiver clock time and are called pseudo-ranges. The resultant four spheres of position would intersect in a single point if there were no clock error. The receiver clock error is then determined algebraically. Because there is only one value of clock error for which the four spheres can be made to intersect at a single point, the user's position solution is thus provided as shown in Figure 1.2. (Herring, 1996, pp. 46-47)

Arranged in six orbital planes with four satellites in each plane, the constellation of GPS satellites consists of twenty-four satellites. This ensures that a minimum of four satellites are always observable by a user anywhere in the world. The satellites are in circular orbits inclined at fifty-five degrees with altitudes of 20,200 km and complete an orbit every twelve hours.

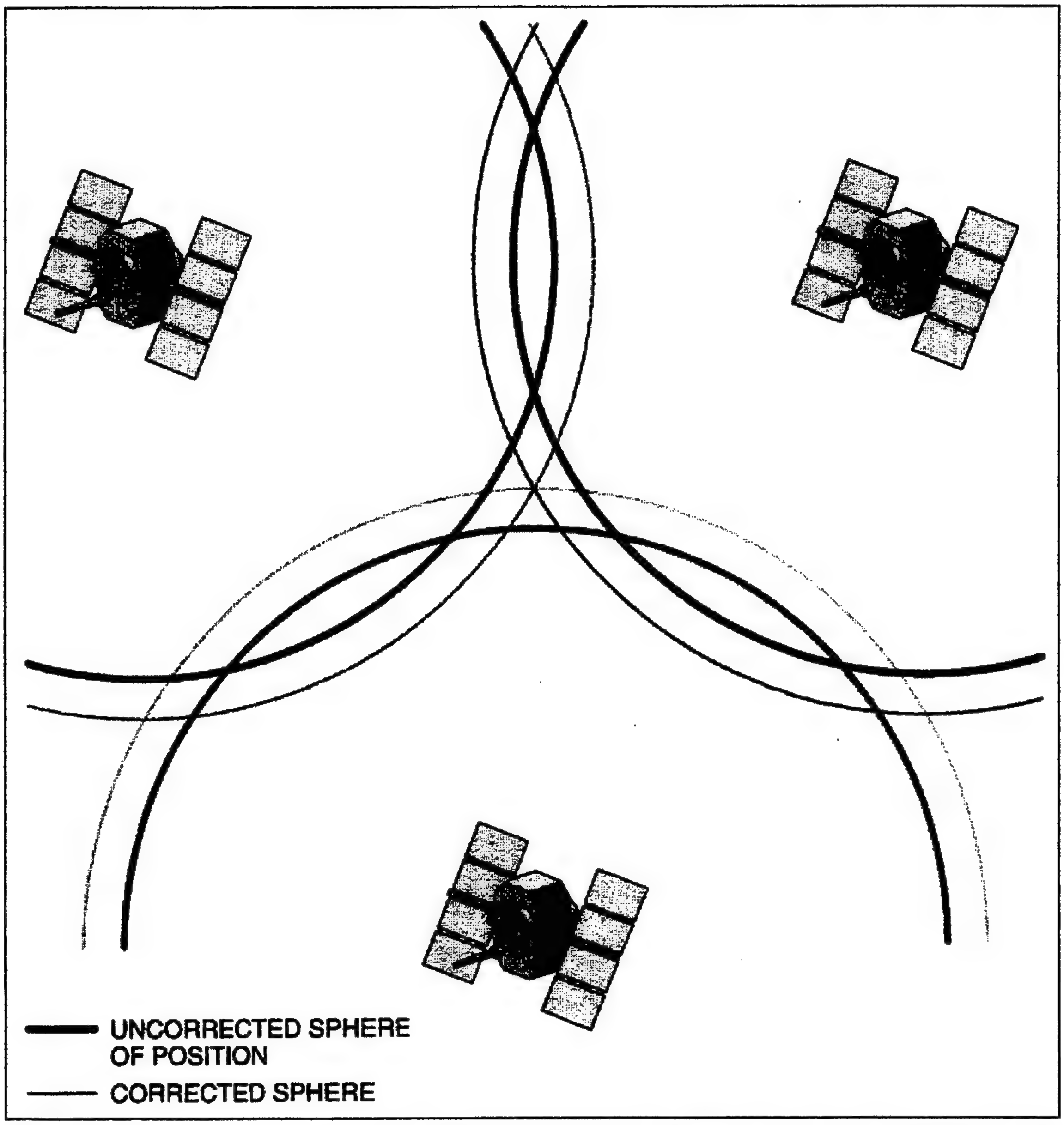
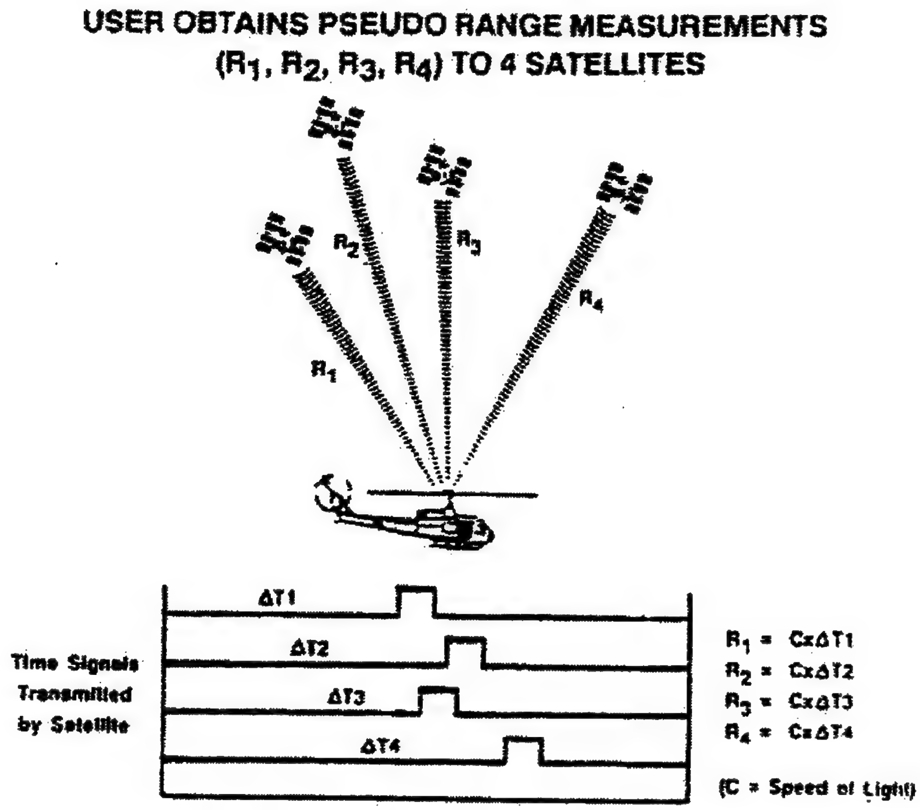


Figure 1.1. Clock error in the receiver causes the range to the GPS satellite to be incorrect. The resulting spheres of position (thick lines) do not intersect at a single point. By adjusting the receiver clock the ranges are corrected and meet at one point (thin lines). In this figure this appears to require three satellites; however, in three dimensions four satellites are required. From Herring, 1996, p. 46.



USER SET PERFORMS THE NAV SOLUTION FOR POSITION

PSEUDO RANGES:	POSITION EQUATIONS:
$R_1 = C\,\Delta t_1$	$(X_1 - U_X)^2 + (Y_1 - U_Y)^2 + (Z_1 - U_Z)^2 = (R_1 - C_B)^2$
$R_2 = C\,\Delta t_2$	$(X_2 - U_X)^2 + (Y_2 - U_Y)^2 + (Z_2 - U_Z)^2 = (R_2 - C_B)^2$
$R_3 = C\,\Delta t_3$	$(X_3 - U_X)^2 + (Y_3 - U_Y)^2 + (Z_3 - U_Z)^2 = (R_3 - C_B)^2$
$R_4 = C\,\Delta t_4$	$(X_4 - U_X)^2 + (Y_4 - U_Y)^2 + (Z_4 - U_Z)^2 = (R_4 - C_B)^2$

R_i = PSEUDO RANGE (i = 1,2,3,4)

- PSEUDO RANGE INCLUDES ACTUAL DISTANCE BETWEEN SATELLITE AND USER PLUS SV CLOCK BIAS, USER CLOCK BIAS, ATMOSPHERIC DELAYS, AND RECEIVER NOISE
- SV CLOCK BIAS AND ATMOSPHERIC DELAYS ARE COMPENSATED FOR BY INCORPORATION OF DETERMINISTIC CORRECTIONS PRIOR TO INCLUSION INTO NAV SOLUTION

X_i, Y_i, Z_i = SATELLITE POSITION (i = 1, 2, 3, 4)

- SATELLITE POSITION BROADCAST IN NAVIGATION 50 Hz MESSAGE

RECEIVER SOLVES FOR:

- U_x, U_y, U_z = USER POSITION
- C_B = USER CLOCK BIAS

Figure 1.2. Navigation Using GPS. From NAVSTAR-GPS Joint Program Office, 1987, p. 1-17.

2. GPS Accuracy

GPS provides two levels of service, the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS). Utilizing spread spectrum techniques, GPS satellites transmit on two L-band frequencies, L1 at 1575.42 MHz and L2 at 1227.6 MHz. Two spreading functions known as C/A-code, or Coarse/Acquisition code, and P-code, or Precise code, are employed. Currently only the C/A-code signal is available to all GPS users and provides the SPS, while the P-code is available to DoD-designated users only and is necessary for the PPS. Although user position can be determined using both codes, only the P-code is transmitted on both frequencies. This enables users with P-code access to perform a dual frequency comparison to compensate for ionospheric effects while C/A code users must rely on a less accurate model of the ionosphere. Satellite ephemeris (orbital element) data, almanac data for finding other satellites in the constellation, atmospheric propagation correction data, satellite clock-bias information, system time and satellite status information are provided by the navigation message which is transmitted on both frequencies. (U.S. Naval Observatory, 1996, pp. 1-2)

Full accuracy is denied to non-DoD designated users through the use of Selective Availability (SA), which modifies the navigation message. SA reduces accuracy by altering the satellite ephemeris data and clock frequency, a procedure which is known as dithering. Anti-spoofing protects against false satellite transmissions by encrypting the P-code, forming the Y-code. (U.S. Naval Observatory, 1996, p. 2)

The SPS has a 95 percent probability of providing horizontal positioning accuracy within 100 meters, vertical positioning accuracy within 156 meters and timing accuracy within 340 nanoseconds. (U. S. Naval Observatory, 1996, p. 1) Typically, one sigma positioning accuracy is on the order of 50 meters horizontally and 75 meters vertically with a velocity accuracy of 50 cm/s. The specification for PPS requires positioning accuracy of 16 meters Spherical Error Probable (SEP) in contrast to the SPS specification of 76 meters SEP and a velocity accuracy of 10 cm/s. A positioning accuracy of 10 meters SEP is usually experienced. (Clynch, 1996) Sources of GPS inaccuracy and their impact are shown in Table 1.1.

Component	Size
Receiver Clock	1000 km
Selective Availability	30 m
Ionosphere	1 - 30 m
Atmosphere	1 - 6 m
Orbit Error	1 - 3 m
Satellite Clock	1 - 3 m
Multipath - C/A Code	0.5 - 150 m
Multipath - P Code	0.1 - 15 m
Receiver Noise	0.1 - 1 m

Table 1.1. GPS Sources of Inaccuracy. From Clynch, 1996.

GPS system time is maintained by the Composite Clock which incorporates all operational Monitor Station and satellite frequency standards. This system time is referenced to the U.S. Naval Observatory's Master Clock within a standard tolerance of one microsecond. Over the last several years GPS system time has maintained a tolerance within a few hundred nanoseconds of the Master Clock. (U.S. Naval Observatory, 1996, p. 3)

B. SHUTTLE GPS

An integrated GPS navigation capability has been developed for the Shuttle. The scheduled replacement of TACAN air navigation stations has been the primary motivating factor in developing this capability. Currently TACAN provides the primary Shuttle entry navigation aid from post blackout to final approach. During final approach through landing the Microwave Scanning Beam Landing System (MSBLS) is the primary navigation aid. Presently, only the orbiter Endeavour is equipped with GPS equipment. The other orbiters will be equipped as they are upgraded.

Two options were considered for integrating GPS into the Shuttle navigation system. The first option was to augment Shuttle entry navigation filters to process GPS

measurements. The second option was for the Shuttle navigation system to process state vector outputs from the GPS receiver. Either option can be extended to other Shuttle mission phases such as ascent and on-orbit operations. The second option of processing GPS state vector outputs was selected because it required fewer software changes and had the minimum impact on current system operation. Additionally, it facilitated the design objective of a phased-development approach which would permit evaluation of GPS receiver performance during flight before it was used as the primary entry navigation aid. (Kachmar et. al., 1993, pp. 313-317) With respect to developmental testing for STS-69, the GPS receiver navigation solution was not available to the orbiter in real time even as a back up. Beginning with STS-79, the navigation data will be processed by the orbiter computers and real-time state vectors will be available during launch and landing.

Using the second approach, a GPS receiver state vector can be used to reset the baseline navigation state. This navigation state reset procedure is similar to a ground state vector uplink with the important difference that the GPS state vector quality assessment is done onboard the Shuttle. In order to be selected for guidance, the GPS state vector must meet a predefined transient tolerance level. Transients can be induced by the Shuttle mission phase environment, the GPS receiver switching between satellites, and periods of satellite reacquisition. The GPS receiver can be provided aiding data by the Shuttle's Inertial Measurement Units (IMU) to assist the receiver in determining its position for acquisition of the GPS satellites. (Kachmar et. al., 1993, p. 317)

The Shuttle was designated as a DoD-authorized user of PPS due to the need to guarantee a minimum level of entry navigation performance during times of national emergency. It was also desired that current off-the-shelf receiver designs be used that complied with the GPS Joint Program Office Requirements Document. (Kachmar et. al., 1993, p. 317) The Collins 3M receiver was selected for installation onboard Endeavour. The five channel 3M receiver tracks four satellites simultaneously while reading the navigation message for the next satellite to be used by the receiver. It is a P-code receiver with position accuracy of 15 meters SEP, velocity accuracy of 10 cm/s, and timing accuracy of 40 nanoseconds. (Collins, 1994) (Nuss, e-mail, 1996) Two antennas are employed to provide maximum coverage for the receiver. The upper-hemi and lower-

hemi antennas are located on the top and bottom of the orbiter respectively as shown in Figure 1.3.

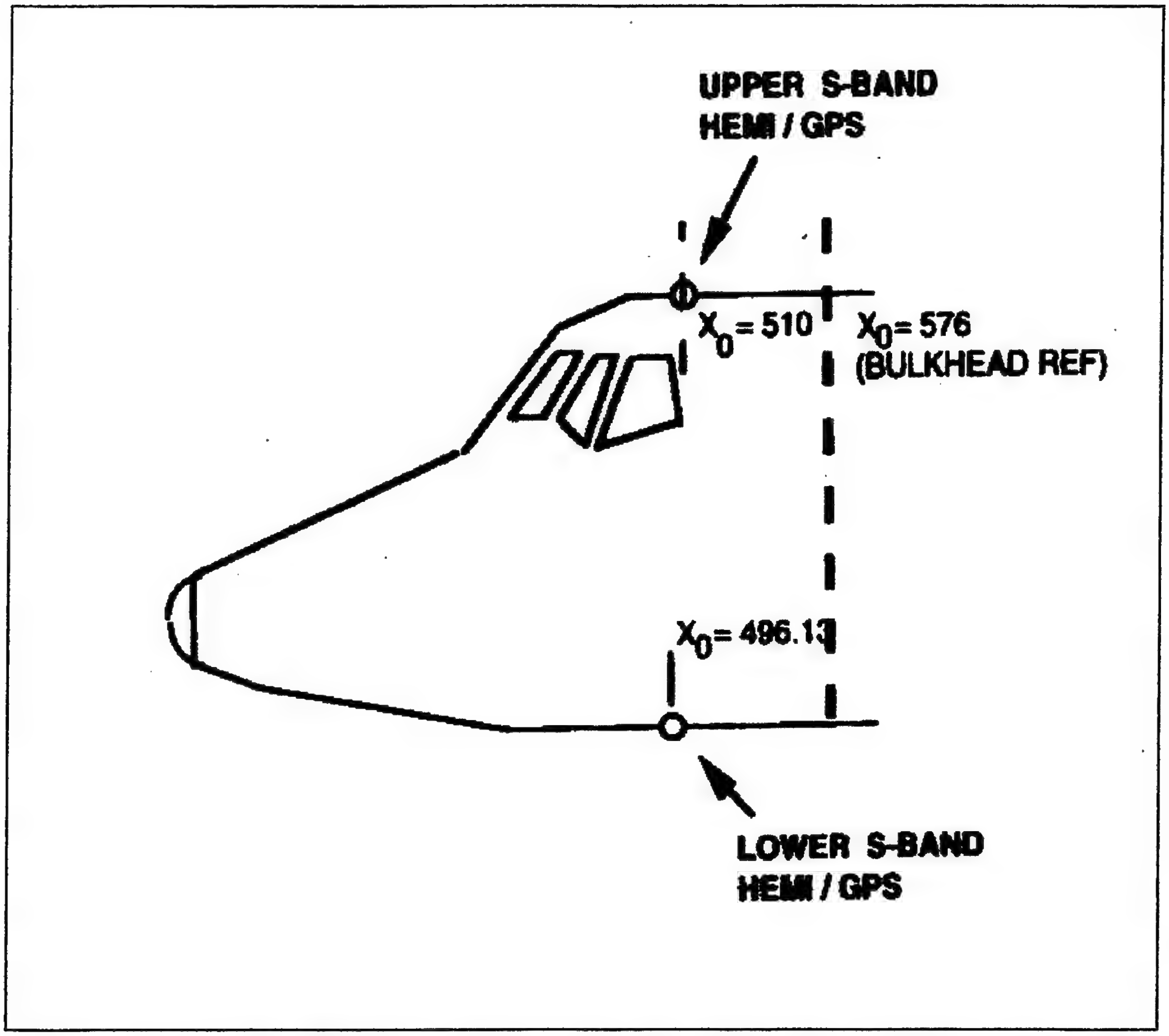


Figure 1.3. Shuttle GPS Antenna Placement. From Carpenter and Hinkel, 1995, p. 6.

C. STS-69

Shuttle mission STS-69 lifted off from Pad 39-A at the Kennedy Space Center (KSC) on September 7, 1995, at 11:09:00.052 a.m. EDT. Endeavour's crew of five included: Commander David M. Walker, Pilot Kenneth D. Cockrell, Payload Commander James S. Voss, Mission Specialist James H. Newman, and Mission Specialist Michael L. Gernhardt. The mission featured the second flight of the Wake Shield Facility (WSF), a four-meter-diameter saucer-shaped free-flying satellite designed to grow semiconductor

films in the ultra-vacuum created in the wake of the satellite as it moves through space. The Spartan 201 free-flying astronomy satellite was also deployed and retrieved. Additionally, the crew tested assembly techniques for the international space station and tested thermal improvements made to space suits used during space walks. On September 18, 1995 at 7:37:56 am EDT, after 10 days, 20 hours, 28 minutes and 55 seconds, STS-69 landed at KSC. After a successful mission and traveling over four and a half million miles, Endeavour touched down on Runway 33 at the KSC Shuttle Landing Facility.

The WSF was employed to conduct several GPS experiments sponsored by the Texas Space Grant Consortium and was equipped with a TurboRogue GPS receiver furnished by the University Corporation for Atmospheric Research (UCAR). University of Texas at Austin researchers and Johnson Space Center personnel conducted the experiments which were aimed at: assessing relative positioning using the TurboRogue receiver on the WSF and Endeavour's Collins 3M receiver, evaluating precision orbit determination in a low-altitude environment (400 km) where perturbations due to atmospheric drag and the Earth's gravity field are more pronounced than for higher altitude satellites such as TOPEX/POSEIDON, and determining atmospheric temperature profiles using GPS signals passing through the atmosphere. (Schutz et. al., 1995, pp 1-2) During STS-69 Endeavour's 3M receiver operated in a SPS mode.

II. REFERENCE FRAMES AND SHUTTLE TRACKING

A. REFERENCE FRAMES

Several reference frames were used when comparing GPS navigation solutions with the reference track. Shuttle navigation and tracking sources utilize the Aries Mean-of-1950 Earth-Centered Inertial reference frame, Greenwich Mean Time and English units. GPS navigation solutions provide position data in the WGS 84 Earth-Centered Earth-Fixed reference frame using Coordinated Universal Time and metric units. GPS velocity data is in a Shuttle Up-East-North frame and in metric untis.

1. Inertial Reference Frames

The Aries Mean-of-1950 (M50) and J2000 Earth-Centered Inertial (ECI) reference frames are not actually fixed with respect to the mean position of the stars in the vicinity of the Sun, or inertial space. These inertial frames are defined by the direction of the Earth's axis of rotation, or celestial pole, and the direction from the Earth to the Sun on the first day of spring which is known as the vernal equinox or first point of Aries. The celestial pole is affected by gravitational forces, primarily those exerted by the Sun and Moon. These forces produce a quasi-conical motion of the mean celestial pole around the pole of the ecliptic, or axis of rotation of the Earth's orbit around the Sun. This lunisolar precessional motion has a period of 26,000 years. The motion of the actual celestial pole around the mean pole is known as nutation and has a period of 18.6 years. (Larson and Wertz, 1992, pp. 94-95) (Seidelmann, 1992, p. 12) The International Astronomical Union (IAU) has adopted conventions for calculating general precession (IAU 1976) (Seidelmann, 1992, p. 103) and general nutation (IAU 1980) (Seidelmann, 1992, p. 111); however, they do not account for transient pole wander.

Motion of the vernal equinox subsequently accompanies the motion of the celestial pole. As a result, in order to define an ECI reference frame the date which specifies the position of the vernal equinox must be established. (Seidelmann, 1992, p. 12) The J2000 frame is a right-handed Cartesian coordinate system with its origin at the center of the

Earth and its X and Z axes pointing towards the mean vernal equinox and mean rotation axis of January 1, 2000. The M50 coordinate system uses the mean vernal equinox and mean rotation axis of 1950 as its reference directions. A constant transformation matrix has been developed to perform the conversion from M50 to J2000 coordinates. (Seidelmann, 1992, pp. 184-187)

2. WGS 84 Reference Frame

The World Geodetic System 1984 (WGS 84) reference frame is a Conventional Terrestrial System (CTS) whose origin is the center of mass of the Earth. The system's Z-axis is parallel to the direction of the Conventional Terrestrial Pole (CTP) defined by the Bureau International de l'Heure (BIH). The X-axis is the intersection of the WGS 84 reference meridian plane, which is parallel to the Zero Meridian defined by the BIH, and the CTP's equatorial plane. The Y-axis completes a right-handed, earth-fixed orthogonal coordinate system. This reference frame rotates with the Earth and assumes that the earth is rotating at a constant rate around a mean celestial pole, the CTP. Variations from this approximation cause the WGS 84 CTS to differ from the true Instantaneous Terrestrial System (ITS) which is rotating around an instantaneous pole, the Celestial Ephemeris Pole (CEP). The WGS 84 CTS can be related to the J2000 Conventional Inertial System (CIS) by Equation 2.1.

$$CTS = [A]\,[B]\,[C]\,[D]\,CIS \tag{2.1}$$

The rotation matrices account for: [A] polar motion, [B] sidereal time, [C] astronomic nutation, and [D] precession. Matrices B, C and D establish the relationship between the CIS and the ITS. The ITS is related to the CTS by matrix A which provides the relationship between the CEP and the CTP. (DMA, 1987, pp. 2-1 - 2-3)

3. Transformation to J2000

The Shuttle navigation system and the NASA Shuttle tracking sources produce state vectors using the M50 ECI reference frame, and GPS state vectors are provided in the WGS 84 Earth-Centered Earth-Fixed (ECEF) reference frame. As shown in Figure 2.1, the M50 frame is fixed in inertial space while the WGS 84 frame rotates with the Earth. In order to compare state vectors from both systems it is necessary to perform a transformation between the two reference frames. This transformation requires an intermediate step of converting the data into the J2000 ECI reference frame. For this reason comparison of state vectors from the two sources was conducted in the J2000 frame.

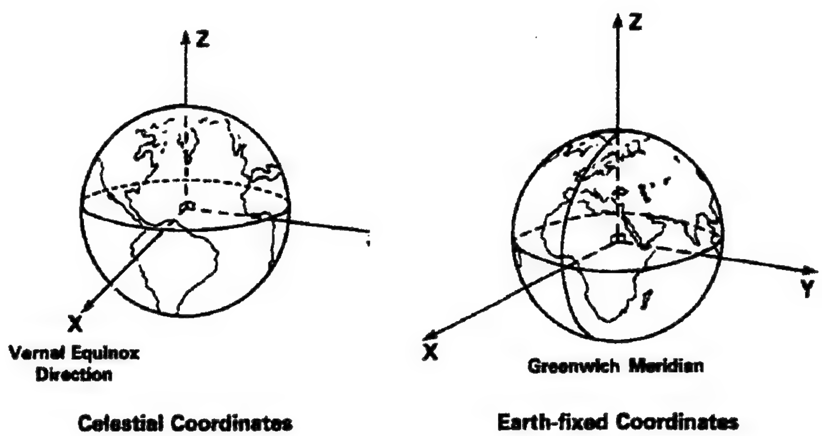


Figure 2.1. ECI and ECEF Coordinate Systems. From Larson and Wertz, 1992, p. 95.

4. Up-East-North Reference Frame

GPS velocity data is provided in the Up-East-North (UEN) reference frame which has its origin fixed with the spacecraft as shown in Figure 2.2. The UEN system can be

visualized using the idea of the Shuttle flying with its belly facing the Earth much like the attitude an aircraft would assume while flying above the surface of the Earth. The Shuttle's nose would point along the velocity vector. Up would be equivalent to altitude above the ground, East would point straight ahead from the nose and North would point in the direction of the left wing tip. Technically, the Up axis is in the radial direction from the center of the Earth. The East axis is in the local orbital downtrack direction and parallels the velocity vector. The North axis is in the crosstrack direction completing a right-handed coordinate system and parallels the orbit normal.

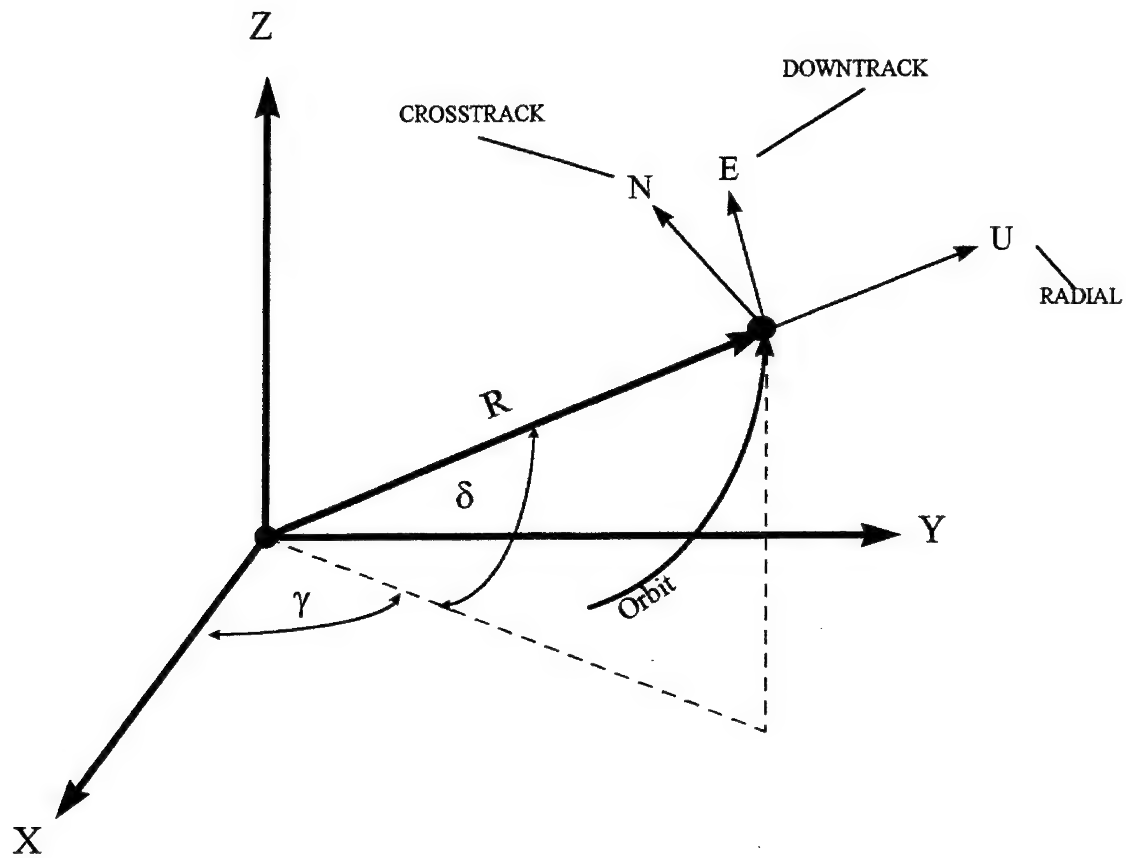


Figure 2.2. Up-East-North Reference Frame.

In order to perform the transformation from the UEN reference frame to the WGS 84 reference frame two Euler angle rotations must be performed. A rotation about the Y-axis by $+\delta$ followed by a rotation about the Z-axis by a value of $-\gamma$ is required as shown in Equations 2.2, 2.3 and 2.4.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{WGS84} = C_Z(-\gamma)\, C_Y(\delta) \begin{bmatrix} U \\ E \\ N \end{bmatrix} \tag{2.2}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{WGS84} = \begin{bmatrix} \cos(-\gamma) & \sin(-\gamma) & 0 \\ -\sin(-\gamma) & \cos(-\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\delta) & 0 & -\sin(\delta) \\ 0 & 1 & 0 \\ \sin(\delta) & 0 & \cos(\delta) \end{bmatrix} \begin{bmatrix} U \\ E \\ N \end{bmatrix} \tag{2.3}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{WGS84} = \begin{bmatrix} \cos(\gamma)\cos(\delta) & -\sin(\gamma) & -\cos(\gamma)\sin(\delta) \\ \sin(\gamma)\cos(\delta) & \cos(\gamma) & -\sin(\gamma)\sin(\delta) \\ \sin(\delta) & 0 & \cos(\delta) \end{bmatrix} \begin{bmatrix} U \\ E \\ N \end{bmatrix} \tag{2.4}$$

This transformation is easily realizable in Fortran and was applied to GPS state vector velocity components.

5. Time

International Atomic Time (TAI) compares several processes of physics such as cesium frequency standards and hydrogen masers to form a standard timescale that can be used to uniquely identify the instance of time at which an event occurs on Earth. (Seidelmann, 1992, p. 2) Universal Time (UT) is based upon the Earth's rotation with respect to the Sun. Since the rotation of the Earth is affected by irregular forces, UT is irregular with respect to TAI. The difference between TAI and UT is increasing irregularly by approximately one second every eighteen months, and this difference is always maintained as an integral number of seconds known as leap seconds. Coordinated Universal Time (UTC) is an atomic timescale that is kept in close agreement with UT through the addition of these leap seconds. (Seidelmann, 1992, pp. 6-7) UTC is the timescale used by GPS and is provided in the receiver navigation solution.

Greenwich Mean Time (GMT) is the basis of civil time for the United Kingdom and is subsequently related to UTC; however, in navigation terminology GMT has been used as UT. As a result, the term GMT is somewhat ambiguous. (Seidelmann, 1992, p. 7) All Shuttle tracking data uses GMT as its timescale. In this specific case, GMT is equivalent to UTC. (Nikolaidis, e-mail, June 1996) In order to facilitate the use of the

coordinate frame transformation program and STK, all times were converted to Mission Elapsed Time (MET) in seconds which starts at the time of launch.

B. SHUTTLE TRACKING

NASA uses two primary sources for Shuttle tracking data, ground sites using C-band radar and Tracking and Data Relay Satellites (TDRS). Several of the NASA tracking sources are listed in Table 2.1. C-band radar sites use range and angle data and TDRS uses doppler measurements to create Shuttle state vectors. Normally two to four state vectors are generated per orbit, although, more vectors are generated during periods of high activity such as rendezvous, translational maneuvers and IMU alignments. With the exclusion of rendezvous, the three sigma position accuracy of the state vectors is 200 m in the radial direction, 450 m in the downtrack direction and 200 m in the crosstrack direction. A three sigma velocity accuracy of 0.45 m/s in the radial direction, 0.20 m/s in the downtrack direction and 0.25 m/s in the crosstrack direction is typically achieved. During quiescent periods, three sigma accuracies of 100 m and 0.30 m/s radially, 250 m and 0.10 m/s downtrack and 100m and 0.15 m/s crosstrack may be obtained. During rendezvous and other highly active periods errors on the order of several kilometers may be experienced. (RSOC, 1996, p 1)

Source	Identifier
East TDRS	ESTR
West TDRS	WSTR
Ascension Island	ASCC
Bermuda	BDQC
Kwajalein Island	KMTC
Wallops Island	WLRC

Table 2.1. NASA Shuttle Tracking Sources.

III. DATA FILES, TOOLS AND PROCEDURE

A. DATA FILES

1. GPS Navigation Solutions

GPS data files from the 3M receiver for each flight day of STS-69, Julian days 250 through 260, were made available by the Johnson Space Center (JSC). There was an average of 60 navigation solution files per day and a total of 660 files. Each file had from 800 to 3300 state vectors with fixes obtained generally every second, although every day had some period of outage with no GPS data. Individual state vector entries contained: GPS system time; Coordinated Universal Time (UTC); position in XYZ WGS 84 ECEF coordinates (m); velocity in UEN coordinates (m/s); position in latitude, longitude and altitude; pitch, roll and heading information; acceleration in UEN coordinates; and receiver health and status information. A typical GPS data file is shown in Figure 3.1.

2. NAVG-11 State Vectors

Rockwell Space Operations Company (RSOC) provided a NAVG-11 Shuttle Navigation Postflight Product which included ground navigation history vectors. The NAVG-11 product contains the orbiter solution vectors which are processed real-time using C-band range and angle data and TDRS doppler data. Each entry contained the batch ID, orbit number, batch number, UTC labeled as Greenwich Mean Time (GMT), and position and velocity in XYZ M50 ECI coordinates (ft and ft/s). There were approximately 430 state vectors for the entire mission in this file. Two to four vectors were provided per orbit with the bulk of the data coming from TDRS. (RSOC, 1996, p. 1) A portion of the NAVG-11 file is shown in Figure 3.2.

3. Propagated State Vectors

RSOC also provided a second more densely propagated data file with over 16,000 state vectors for the entire mission. The first column of the propagated file is Mission Elapsed Time (MET) in hours from launch which was given to be 1995:250:15:09:00.0 GMT. The program that produces the denser ephemeris propagates from vector to vector using a Nystrom-Lear fourth order integrator for both position and velocity. Four derivative evaluations are required for each 60 second integration step. The program takes into account modeled translational maneuvers, Sun and Moon induced gravitational perturbations, drag computed using a Jacchia 1970 atmosphere model, and a 7x7 gravitational potential model. Figure 3.3 shows a small portion of the propagated data file. (Nikolaidis, e-mail, March 1996)

B. TOOLS

1. File Transfer Protocol

All analysis was performed on a Silicon Graphics Indigo II workstation. File Transfer Protocol (FTP) provided the only manageable means for retrieving the GPS data files from the JSC server. The large number and size of the files made the option of copying them to some form of media for transfer unattractive.

2. Unix Scripts

Unix scripts, sequences of Unix commands that can be stored in files, were employed in editing all the data files and were crucial in the editing of the GPS data files. Hand editing all the data files was not feasible, and the Unix scripts proved to be the only way to deal with the large quantity of data files by automating the procedure of uncompressing and compressing files, grouping files by day, editing files and executing Fortran programs. More specifically, the Stream Editor (SED) command made the

analysis of the enormous amount of data possible. It provided an automated means for removing text headers and troublesome characters such as colons and slashes.

```
GPS UTC ECEF_X ECEF_Y ECEF_Z VEL_E VEL_N VEL_U LAT LON ALT_MSL ALT_ABS PITCH ROLL HEADING ACCEL_E
ACCEL_N ACCEL_U CH1FAULT CH1FREQ CH1CODE CH1STATE CH1HWCH CH1PRN CH1SNR CH1JS CH2FAULT CH2FREQ
CH2CODE CH2STATE CH2HWCH CH2PRN CH2SNR CH2JS CH3FAULT CH3FREQ CH3CODE CH3STATE CH3HWCH CH3PRN
CH3SNR CH3JS CH4FAULT CH4FREQ CH4CODE CH4STATE CH4HWCH CH4PRN CH4SNR CH4JS CH5FAULT CH5FREQ
CH5CODE CH5STATE CH5HWCH CH5PRN CH5SNR CH5JS FOM HERR VERR STATE5 STATE3 LESS4 IN_VAL IN_HV TFOM
35191.207853 95:253/09:46:21 -5402333.500000 2444969.000000 -3208548.250000 7258.089844 -180.840454 -3.660278 S28:34:10.72
E155:38:58.61 368933.156250 368968.062500 0.000000 0.000000 0.000000 0.0579615 0.5219483 -7.7938795 0 L1 C/A 5 5 24 42 0 0 L1
C/A 5 2 6 43 0 0 L1 C/A 5 3 9 42 0 0 L1 C/A 0 4 5 0 0 0 L1 C/A 0 1 16 0 0 5 67 85 N N Y N N 4
35192.207853 95:253/09:46:22 -5405241.000000 2438317.750000 -3208703.500000 7258.228516 -176.069733 -3.639641 S28:34:16.21
E155:43:11.09 368929.218750 368964.156250 0.000000 0.000000 0.000000 0.0581555 0.5306978 -7.7542396 0 L1 C/A 5 5 24 42 0 0 L1
C/A 5 2 6 43 0 0 L1 C/A 5 3 9 42 0 0 L1 C/A 3 4 5 0 0 0 L1 C/A 1 1 16 0 0 5 67 85 N N Y N N 4
35193.207853 95:253/09:46:23 -5408142.000000 2431664.250000 -3208854.500000 7258.343750 -171.306320 -3.680504 S28:34:21.56
E155:47:23.56 368924.968750 368959.906250 0.000000 0.000000 0.000000 0.0414648 0.4980080 -7.8656659 0 L1 C/A 5 5 24 42 0 0 L1
C/A 5 2 6 42 0 0 L1 C/A 5 3 9 42 0 0 L1 C/A 7 4 5 0 0 0 L1 C/A 1 1 16 0 0 5 67 86 N N Y N N 4
35194.207853 95:253/09:46:24 -5411037.000000 2425008.000000 -3209001.500000 7258.449219 -166.527313 -3.629784 S28:34:26.77
E155:51:35.99 368920.656250 368955.593750 0.000000 0.000000 0.000000 0.0119982 0.5229011 -7.8359241 0 L1 C/A 5 5 24 42 0 0 L1
C/A 5 2 6 42 0 0 L1 C/A 5 3 9 42 0 0 L1 C/A 0 4 5 0 0 0 L1 C/A 1 1 16 0 0 5 67 86 N N Y N N 4
35195.207853 95:253/09:46:25 -5413926.000000 2418349.250000 -3209144.000000 7258.584473 -161.753922 -3.604240 S28:34:31.83
E155:55:48.52 368916.406250 368951.343750 0.000000 0.000000 0.000000 0.0278492 0.5446374 -7.7630706 0 L1 C/A 5 5 24 43 0 0 L1
C/A 5 2 6 42 0 0 L1 C/A 5 3 9 42 0 0 L1 C/A 1 4 5 0 0 0 L1 C/A 1 1 16 0 0 5 67 86 N N Y N N 4
35196.207853 95:253/09:46:26 -5416809.000000 2411687.500000 -3209281.750000 7258.655273 -156.993515 -3.555328 S28:34:36.71
E156:00:00.99 368912.093750 368947.031250 0.000000 0.000000 0.000000 -0.0142004 0.5663438 -7.6834655 0 L1 C/A 5 5 24 43 0 0 L1
C/A 5 2 6 42 0 0 L1 C/A 5 3 9 41 0 0 L1 C/A 1 4 5 0 0 0 L1 C/A 1 1 16 0 0 5 67 86 N N Y N N 4
35197.207853 95:253/09:46:27 -5419686.500000 2405023.250000 -3209415.250000 7258.793457 -152.230057 -3.538269 S28:34:41.45
E156:04:13.47 368907.781250 368942.750000 0.000000 0.000000 0.000000 -0.0094650 0.5297642 -7.7330899 0 L1 C/A 5 5 24 43 0 0 L1
C/A 5 2 6 42 0 0 L1 C/A 5 3 9 41 0 0 L1 C/A 1 4 5 0 0 0 L1 C/A 1 1 16 0 0 5 67 86 N N Y N N 4
35198.207853 95:253/09:46:28 -5422558.000000 2398355.750000 -3209545.250000 7258.930664 -147.459351 -3.592278 S28:34:46.06
E156:08:26.00 368903.843750 368938.812500 0.000000 0.000000 0.000000 0.0435655 0.5438979 -7.7969489 0 L1 C/A 5 5 24 43 0 0 L1
C/A 5 2 6 42 0 0 L1 C/A 5 3 9 41 0 0 L1 C/A 7 4 5 0 0 0 L1 C/A 1 1 16 0 0 5 67 86 N N Y N N 4
35199.207853 95:253/09:46:29 -5425424.000000 2391686.000000 -3209671.250000 7259.022949 -142.694702 -3.582455 S28:34:50.52
E156:12:38.52 368900.625000 368935.593750 0.000000 0.000000 0.000000 0.0238013 0.5525908 -7.7608609 0 L1 C/A 5 5 24 43 0 0 L1
C/A 5 2 6 42 0 0 L1 C/A 5 3 9 41 0 0 L1 C/A 0 4 5 0 0 0 L1 C/A 5 1 16 44 0 5 67 86 N N Y N N 4
35200.207853 95:253/09:46:30 -5428284.000000 2385014.000000 -3209793.000000 7259.140625 -137.965729 -3.629726 S28:34:54.83
E156:16:51.05 368897.312500 368932.281250 0.000000 0.000000 0.000000 0.0451047 0.5006838 -7.8411965 0 L1 C/A 5 5 24 43 0 0 L1
C/A 5 2 6 42 0 0 L1 C/A 5 3 9 40 0 0 L1 C/A 1 4 5 0 0 0 L1 C/A 5 1 16 44 0 5 67 86 N N Y N N 4
```

Figure 3.1. GPS Navigation Solution Data File.

FLT : STS-069

VAT VECTOR TABLE

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STATION ORBIT	BATCH NO.	ANCHOR TIME GMT (DDD:HH:MM:SS)	X (ft)	Y (ft)	Z (ft)	X-DOT (ft/sec)	Y-DOT (ft/sec)	Z-DOT (ft/sec)	HA (n.mi)	HP (n.mi)
MECO001	0001	250:15:18:34	-16926520.083	8501141.595	9738813.949	-13525.554005	-21821.400678	-3510.911155	195.791	34.839
OMS2001	0002	250:15:54:00	6719216.338	-18626836.267	-9895185.751	22548.406454	10446.404870	-4351.659562	200.712	199.253
WSTR001	0013	250:16:09:53	20644097.920	-579150.472	-7980997.160	3750.749653	23639.464094	7967.308126	201.065	199.055
BDQC002	0014	250:16:49:36	-17433871.248	9127119.056	10149250.788	-13159.120575	-21227.787530	-3518.294146	200.236	199.488
WLRC002	0015	250:16:49:54	-17667070.536	8743127.430	10083682.687	-12749.310510	-21436.479924	-3754.934819	200.228	199.486
ESTR002	0016	250:16:55:48	-20642663.635	657736.367	7979505.897	-3832.827190	-23624.031440	-7971.778459	200.161	199.760
WSTR002	0018	250:17:38:53	19599708.731	-4684770.337	-9167984.077	8351.878159	23013.828305	6080.178671	200.799	198.981
ESTR003	0019	250:18:36:30	-18956571.489	-11151315.483	2551657.620	10127.539269	-19900.989239	-11745.186829	200.475	199.895
WSTR003	0020	250:19:17:24	20857827.706	4571263.114	-5857782.333	-2206.772296	23018.113114	10084.669242	200.870	199.303
ESTR004	0021	250:20:12:16	-16013047.418	-15287188.742	-296492.917	15408.545211	-15902.437856	-12095.115378	200.612	199.791
WSTR005	0022	250:20:58:30	15764514.699	15541036.714	538136.446	-15754.257707	15564.609075	12082.065588	200.505	199.854
ESTR005	0023	250:21:52:05	-6792871.628	-20263903.590	-5777552.334	22620.253441	-4686.989242	-10144.060257	200.639	199.489
WSTR006	0024	250:22:34:20	11562194.267	18576749.482	3398908.126	-19961.089624	10327.048701	11457.985016	200.418	199.740
ESTR006	0025	250:23:31:43	4121362.627	-19563775.430	-9505449.013	23467.457833	7549.369495	-5357.846958	200.354	199.369
WSTR007	0026	251:00:12:57	2632424.683	20648875.160	7549806.127	-23750.990020	-79.083184	8492.510063	200.384	199.391
ESTR007	0027	251:01:08:15	10315521.882	-16531231.474	-10504749.902	20877.595275	14065.998509	-1633.446295	200.220	199.332
WSTR008	0028	251:01:50:49	-5831499.493	18922423.996	9910151.290	-23025.192893	-9351.199729	4302.970710	200.250	199.203
ESTR008	0029	251:02:45:56	16576697.732	-10520113.662	-10226678.568	14784.386970	20190.826172	3188.040552	200.403	199.183
WSTR009	0030	251:03:28:21	-12988728.139	14463474.574	10600076.382	-18885.853730	-16712.183645	-339.493320	200.155	199.216
ESTR009	0031	251:04:23:54	20414306.006	-2518031.386	-8186709.705	5958.669806	23279.015877	7684.501153	200.736	199.097
WSTR010	0032	251:05:05:49	-18222754.135	8002907.276	9701904.076	-12082.686294	-21595.353605	-4880.813268	200.080	199.337
ESTR010	0033	251:06:01:09	20957337.301	4922067.366	-5170135.523	-2732.162928	22750.012842	10559.517965	200.830	199.161
WSTR011	0034	251:06:43:42	-20956718.095	-165617.468	7143923.358	-2861.352228	-23415.012276	-8937.215862	200.100	199.577

Figure 3.2. NAVG-11 State Vector Data File.

0.159444	-0.1692652E+08	0.8501142E+07	0.9738814E+07	-0.1352555E+05	-0.2182140E+05	-0.3510911E+04
0.175718	-0.1767599E+08	0.7202613E+07	0.9508921E+07	-0.1205088E+05	-0.2249043E+05	-0.4333623E+04
0.175996	-0.1768802E+08	0.7180117E+07	0.9504580E+07	-0.1202534E+05	-0.2250100E+05	-0.4347434E+04
0.176273	-0.1770004E+08	0.7157611E+07	0.9500226E+07	-0.1199978E+05	-0.2251153E+05	-0.4361238E+04
0.176551	-0.1771202E+08	0.7135094E+07	0.9495858E+07	-0.1197421E+05	-0.2252202E+05	-0.4375034E+04
0.176829	-0.1772398E+08	0.7112567E+07	0.9491476E+07	-0.1194862E+05	-0.2253249E+05	-0.4388823E+04
0.177107	-0.1773592E+08	0.7090029E+07	0.9487080E+07	-0.1192302E+05	-0.2254292E+05	-0.4402605E+04
0.177384	-0.1774783E+08	0.7067481E+07	0.9482671E+07	-0.1189740E+05	-0.2255331E+05	-0.4416380E+04
0.177662	-0.1775972E+08	0.7044922E+07	0.9478247E+07	-0.1187177E+05	-0.2256368E+05	-0.4430147E+04
0.177940	-0.1777157E+08	0.7022354E+07	0.9473810E+07	-0.1184612E+05	-0.2257401E+05	-0.4443907E+04
0.178218	-0.1778341E+08	0.6999774E+07	0.9469360E+07	-0.1182045E+05	-0.2258430E+05	-0.4457660E+04
0.178496	-0.1779522E+08	0.6977185E+07	0.9464895E+07	-0.1179477E+05	-0.2259457E+05	-0.4471405E+04
0.178773	-0.1780700E+08	0.6954585E+07	0.9460417E+07	-0.1176908E+05	-0.2260480E+05	-0.4485143E+04
0.179051	-0.1781875E+08	0.6931975E+07	0.9455925E+07	-0.1174336E+05	-0.2261499E+05	-0.4498874E+04
0.179329	-0.1783048E+08	0.6909355E+07	0.9451419E+07	-0.1171764E+05	-0.2262516E+05	-0.4512597E+04
0.179607	-0.1784219E+08	0.6886725E+07	0.9446900E+07	-0.1169190E+05	-0.2263529E+05	-0.4526313E+04
0.179884	-0.1785387E+08	0.6864085E+07	0.9442366E+07	-0.1166614E+05	-0.2264538E+05	-0.4540021E+04
0.180162	-0.1786552E+08	0.6841434E+07	0.9437819E+07	-0.1164037E+05	-0.2265545E+05	-0.4553722E+04
0.180440	-0.1787715E+08	0.6818774E+07	0.9433259E+07	-0.1161458E+05	-0.2266548E+05	-0.4567415E+04
0.180718	-0.1788875E+08	0.6796103E+07	0.9428685E+07	-0.1158878E+05	-0.2267547E+05	-0.4581101E+04
0.180996	-0.1790033E+08	0.6773423E+07	0.9424097E+07	-0.1156296E+05	-0.2268543E+05	-0.4594779E+04
0.181273	-0.1791188E+08	0.6750733E+07	0.9419495E+07	-0.1153713E+05	-0.2269536E+05	-0.4608450E+04
0.181551	-0.1792340E+08	0.6728032E+07	0.9414880E+07	-0.1151128E+05	-0.2270526E+05	-0.4622113E+04
0.181829	-0.1793490E+08	0.6705322E+07	0.9410251E+07	-0.1148541E+05	-0.2271512E+05	-0.4635768E+04
0.182107	-0.1794637E+08	0.6682602E+07	0.9405608E+07	-0.1145954E+05	-0.2272495E+05	-0.4649416E+04
0.182384	-0.1795782E+08	0.6659872E+07	0.9400952E+07	-0.1143364E+05	-0.2273475E+05	-0.4663056E+04
0.182662	-0.1796924E+08	0.6637133E+07	0.9396282E+07	-0.1140774E+05	-0.2274451E+05	-0.4676689E+04
0.182940	-0.1798063E+08	0.6614383E+07	0.9391599E+07	-0.1138181E+05	-0.2275423E+05	-0.4690313E+04

Figure 3.3. Propagated Data File.

3. Fortran Programs

Fortran programs proved to be very versatile and effective in dealing with the varying data files. They were used to select the desired state vector elements from the input file line entries, convert the input file times to MET in seconds, and write the new data files. In the case of the GPS data files, Fortran programs were also used to thin the dense GPS data files by a factor of ten and transform GPS UEN velocity data into WGS 84 coordinates. Fortran routines also converted all the NAVG-11 and propagated data from English units to metric units.

4. Satellite Tool Kit

Satellite Tool Kit (STK) is an orbit analysis software package developed by Analytical Graphics that employs an object paradigm. A Graphical User Interface (GUI) is used to manipulate objects such as scenarios, vehicles, facilities, targets, and sensors. This thesis required work with only scenarios and vehicles. A vehicle is defined as a movable land, sea, air or space object. A scenario is a set of objects that is to be visualized. The objects in the scenario are related by time to a map background which provides a geographic reference frame. (Analytical Graphics, 1996, pp. 1-2) STK Vehicle files for the Shuttle were created using GPS ephemeris data and the propagated file ephemeris data and incorporated into scenarios for visualization.

5. ConvertTool

The STK math utility convertTool provided a means for transforming data files from one reference frame to another. In particular it permitted files to be transformed from M50 to J2000, J2000 to M50, ECEF to J2000, and J2000 to ECEF. The program accounts for general precession according to IAU 1976 and general nutation according to IAU 1980. It does not account for the Earth's irregular rotation rate or pole wander. (Woodburn, e-mail, 1996)

6. Matlab

Matlab is an interactive numerical computation, data analyis and plotting software package. The basic Matlab data element is a matrix, and it uses matrix manipulation to perform many numeric calculations in a fraction of the time it would take to write and run a program in a language such as Fortran which would perform the same function. Matlab allows the execution of sequences of commands that can be stored in files called M-files. Matlab was used extensively to compare GPS data and Shuttle reference track data.

C. PROCEDURE

Upon undertaking a project with such a large amount of data, procedures needed to be established to facilitate the transfer and manipulation of the vast data sets. From the beginning, using File Transfer Protocol to retrieve the data, to the end, using Matlab to perform major coordinate transformations, the emphasis was on using computer programs and tools to simplify all aspects of working with the data. The procedure and tools utilized in working with the data is outlined in the flow chart in Figure 3.4.

1. Obtain Data Files

File Transfer Protocol (FTP) was employed to retrieve the 660 GPS data files from the JSC server. The more manageable NAVG-11 and propagated files were obtained on floppy disk and 8 mm tape, respectively. Grouping the files by flight day provided the most efficient way of handling the data. The best results were achieved by plotting each day's worth of data in both STK and Matlab.

2. Edit GPS Files with Unix Scripts and Fortran Program

a. Automation with Unix Scripts

The next step was to edit and manipulate the files using Unix scripts and Fortran programs. The following Unix script, "thinfiles," was invoked to execute the

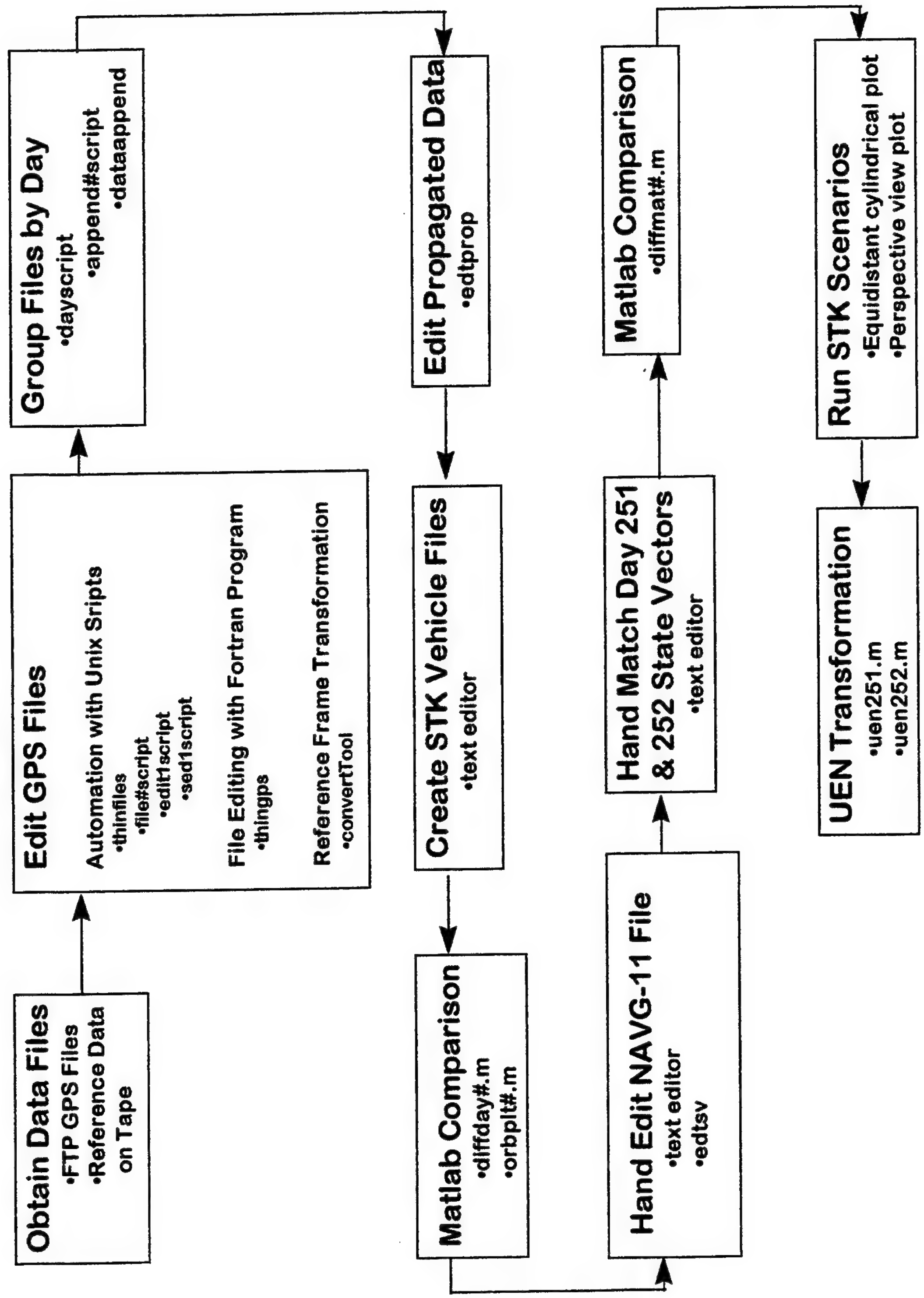


Figure 3.4. Procedure Flow Chart.

scripts and the Fortran program that would manipulate all 660 GPS data files for flight days 250 through 260.

thinfiles

```
file0script
file1script
file2script
file3script
file4script
file5script
file6script
file7script
file8script
file9script
file60script
```

Each file#script in "thinfiles" executed the "edit1script" script for all the GPS data files in each flight day where # was the last digit in the Julian date.

file1script

```
edit1script 251001
edit1script 251002
edit1script 251003
edit1script 251004
.
.
.
edit1script 251086
```

The "edit1script" Unix script was the most important script. It uncompressed and compressed the raw data files, ran the stream editor command, executed the Fortran program, invoked convertTool and created the new edited data files.

edit1script

```
uncompress $1.sol                    - uncompresses raw data files
sed -f sed1script $1.sol > dat.edt   - runs stream editor and creates data file
a.out                                - executes Fortran program
cp out.ecf $1.ecf                    - copies Fortran program output to new file
convertTool <out.ecf> $1.j20         - invokes convertTool program
rm dat.edt                           - removes intermediary data file
rm out.ecf                           - removes intermediary data file
compress $1.sol                      - compresses raw data file for storage
```

The stream editor command eliminated countless hours of hand editing for the raw GPS data files by providing an automated way of removing unwanted file header lines and troublesome colons and slashes. The script "sed1script" is called by the SED command and contains the editing commands that were desired to be performed.

sed1script

/GPS/d	*- deletes file header line which contains the character string GPS*
s/:/ /g	*- replaces all colons with spaces*
s!/! !g	*- replaces all slashes with spaces*

b. File Editing with Fortran Program

The Fortran program "thingps" removed the desired state vector elements from the edited input file, converted time to MET in seconds, transformed GPS UEN velocity data into WGS 84 coordinates, created the new data files, wrote file header information required to execute convertTool and thinned the GPS data files by a factor of ten. An example of the output from "thingps" is shown in Figure 3.5.

thingps.f

```
program thingps
implicit none                                    - declare variables
double precision x,y,z,velx,vely,velz,velup,veleast,velnorth
double precision gps
integer yr,doy,hr,min,sec,mo,day
integer year,dayoyear,month,dayomon,hour,minute,second
integer tmission,secs
integer i,count,i1

open(5,file='dat.edt',status='old')              - open edited data file
rewind(5)
open(6,file='out.ecf',status='unknown')          - open new data file
rewind(6)

year=1995                                        - data required for convertTool
dayoyear=250                                       header and MET conversion
month=09
dayomon=07
hour=15
minute=9
second=0
tmission=dayoyear*24*3600+hour*3600+minute*60+second
```

```
      write(*,1) 3                                    - convertTool header information
1     format(i1)
      write(*,2) year,month,dayomon,hour,minute,second
2     format(i4,5(5x,i2))

      count=0
      do 100 i=1,90000
            read (5,*,end=200) gps,yr,doy,hr,min,sec,x,y,z,       - read desired data
  %                  veleast,velnorth,velup

            secs=(doy*24*3600+hr*3600+min*60+sec)-tmission   - MET conversion

            call uen(x,y,z,velup,veleast,velnorth,velx,vely,velz)

            i1 = i/10*10                              - thin data files by factor of ten
            if (i.eq.i1) then
                  write(6,3) secs,x,y,z,velx,vely,velz
            end if

            count=count+1
100   continue
200   continue
      close(5)
      close(6)
3     format(i7,6(2x,f16.6))
      end

      subroutine uen(x,y,z,velup,veleast,velnorth,velx,vely,velz)   - velocity conversion
      implicit none
      double precision x,y,z,velup,veleast,velnorth
      double precision R,gamma,d,delta,velx,vely,velz

      R=(x**2+y**2+z**2)**0.5                         - elements required for conversion
      gamma=atan2(y,x)                                 (see UEN reference frame section)
      d=(x**2+Y**2)**0.5
      delta=atan2(z,d)

      velx=cos(gamma)*cos(delta)*velup-sin(gamma)*veleast-cos(gamma)   -velocity
  %         *sin(delta)*velnorth                                        components
      vely=sin(gamma)*cos(delta)*velup+cos(gamma)*veleast-
  %         sin(gamma)*sin(delta)*velnorth
      velz=sin(delta)*velup+cos(delta)*velnorth

      return
      end
```

```
3
1995    9    7   15    9    0
210311 -5807460.500000 2664180.500000 2176750.250000 -3617.160579 -5682.921290 -2699.183960
210321 -5843345.000000 2607224.500000 2149632.250000 -3550.238149 -5711.705367 -2727.319201
210331 -5878552.000000 2549989.250000 2122243.000000 -3482.724175 -5739.368855 -2754.648349
210341 -5913083.000000 2492465.750000 2094568.250000 -3414.728305 -5767.289312 -2782.440338
210351 -5946930.500000 2434681.000000 2066630.625000 -3346.832178 -5793.825754 -2809.230668
210361 -5980094.000000 2376616.750000 2038412.750000 -3277.780789 -5820.252935 -2836.150714
210371 -6012572.000000 2318300.250000 2009934.750000 -3208.775076 -5845.790814 -2862.459558
210381 -6044357.000000 2259730.750000 1981197.750000 -3139.212939 -5870.632933 -2888.382278
210391 -6075445.500000 2200916.750000 1952198.750000 -3069.546650 -5894.845623 -2913.939735
210401 -6105832.000000 2141864.000000 1922951.375000 -2999.241909 -5918.394634 -2939.087542
210411 -6135517.000000 2082577.375000 1893451.125000 -2928.762685 -5941.243296 -2963.837522
210421 -6164485.000000 2023086.000000 1863722.125000 -2858.192197 -5963.514047 -2988.293090
210431 -6192744.000000 1963352.500000 1833731.875000 -2787.124061 -5985.066695 -3012.317079
210441 -6220296.500000 1903407.375000 1803503.250000 -2715.831957 -6005.935494 -3035.946644
210451 -6247137.000000 1843254.125000 1773040.625000 -2644.163972 -6026.174693 -3059.191224
210461 -6273259.000000 1782905.125000 1742348.250000 -2572.204979 -6045.666258 -3081.988929
210471 -6298660.000000 1722362.125000 1711434.625000 -2499.826139 -6064.440179 -3104.781688
210481 -6323337.500000 1661633.125000 1680291.375000 -2427.255369 -6082.580226 -3126.816203
210491 -6347287.000000 1600726.625000 1648929.500000 -2354.392636 -6100.067371 -3148.386141
210501 -6370505.500000 1539647.750000 1617353.375000 -2281.315072 -6116.868974 -3169.524312
210511 -6392991.000000 1478401.875000 1585566.250000 -2207.931683 -6133.009991 -3190.278333
210521 -6414739.500000 1416999.750000 1553573.125000 -2134.300879 -6148.461210 -3210.632117
210531 -6435752.500000 1355440.375000 1521381.625000 -2060.593048 -6163.540477 -3230.281239
210542 -6458011.500000 1287567.875000 1485721.000000 -1979.079758 -6179.089416 -3251.691879
210552 -6477475.000000 1225719.000000 1453115.375000 -1904.634163 -6192.343606 -3270.739941
210562 -6496188.000000 1163740.500000 1420325.375000 -1829.840461 -6204.868288 -3289.326550
210572 -6514148.500000 1101638.375000 1387347.875000 -1754.966810 -6216.760793 -3307.496859
210582 -6531357.000000 1039421.187500 1354190.875000 -1679.842193 -6227.969776 -3325.235704
```

Figure 3.5. Output File from thingps.f.

c. *Reference Frame Transformation Using ConvertTool*

The convertTool program transformed the Fortran output file "out.ecf" from ECEF coordinates to J2000 coordinates producing a file with the extension ".j20". The "out.ecf" header "3" corresponds to this conversion to J2000, and a "1" would correspond to a conversion from M50 coordinates to J2000 coordinates. ConvertTool also requires a start time, or epoch, in the file header when converting to or from ECEF coordinates. This start time was selected to be the time of launch in order to comply with the MET convention. Figure 3.6 shows an example output file from convertTool in J2000 coordinates.

3. Group GPS Files by Day

After editing the raw GPS data files and creating the new files with time in MET and position and velocity in J2000 XYZ coordinates, the Unix script "daysscript" was utilized to group the data files by day. First, empty files were created for each day and labeled "gpsday#," where # was equal to the last digit of the Julian date. Next, "daysscript" moved the empty files to a temporary file, "gps.j20," for editing by the "append#script." The "Append#scipt" invoked the script "dataappend" to append sequentially all the files for a flight day to create a single file. Finally, the edited files were moved back to the appropriate "gpsday#" file.

<u>Daysscript</u>

```
mv gpsday0.j20 gps.j20
append0script
mv gps.j20 gpsday0.j20
mv gpsday1.j20 gps.j20
append1script
mv gps.j20 gpsday1.j20
.
.
.
mv gpsday60.j20 gps.j20
append60script
mv gps.j20 gpsday60.j20
```

<u>append1script</u>

```
dataappend 251001
dataappend 251002
dataappend 251003
.
.
.
dataappend 251086
```

<u>dataappend</u>

```
cp $1.j20 data.j20
cat data.j20 >> gps.j20
```

```
210311.000000 -6.2407703666e+06 1.3740186756e+06 2.1742940824e+06 -2.4309569719e+03 -6.7748870446e+03 -2.7004089351e+03
210321.000000 -6.2647246453e+06 1.3061895678e+06 2.1471639724e+06 -2.3498802820e+03 -6.7922414017e+03 -2.7285122487e+03
210331.000000 -6.2878617448e+06 1.2381978524e+06 2.1197629347e+06 -2.2684314772e+03 -6.8082076223e+03 -2.7558092689e+03
210341.000000 -6.3101808750e+06 1.1700361360e+06 2.0920767192e+06 -2.1864248151e+03 -6.8241539588e+03 -2.7835689053e+03
210351.000000 -6.3316801824e+06 1.1017340631e+06 2.0641279529e+06 -2.1047830493e+03 -6.8386012229e+03 -2.8103269743e+03
210361.000000 -6.3523549742e+06 1.0332755883e+06 2.0358992620e+06 -2.0220075353e+03 -6.8525245321e+03 -2.8372142847e+03
210371.000000 -6.3722093663e+06 9.6468937592e+05 2.0074107710e+06 -1.9394426781e+03 -6.8654195619e+03 -2.8634904400e+03
210381.000000 -6.3912356318e+06 8.9597798836e+05 1.9786636079e+06 -1.8564608174e+03 -6.8773446978e+03 -2.8893802682e+03
210391.000000 -6.4094319619e+06 8.2715216914e+05 1.9496547740e+06 -1.7734916060e+03 -6.8884620230e+03 -2.9149048088e+03
210401.000000 -6.4267940241e+06 7.5822047496e+05 1.9203978963e+06 -1.6900232767e+03 -6.8986212922e+03 -2.9400194638e+03
210411.000000 -6.4433231737e+06 6.8918923329e+05 1.8908884745e+06 -1.6065188358e+03 -6.9078873179e+03 -2.9647362445e+03
210421.000000 -6.4590104996e+06 6.2009201310e+05 1.8611506383e+06 -1.5230367302e+03 -6.9163971097e+03 -2.9891585945e+03
210431.000000 -6.4738554438e+06 5.5089231133e+05 1.8311518868e+06 -1.4392102123e+03 -6.9239244413e+03 -3.0131491910e+03
210441.000000 -6.4878669964e+06 4.8162103644e+05 1.8009150923e+06 -1.3553027379e+03 -6.9305631333e+03 -3.0367452985e+03
210451.000000 -6.5010404366e+06 4.1228457367e+05 1.7704446321e+06 -1.2711563350e+03 -6.9363318964e+03 -3.0599562930e+03
210461.000000 -6.5133720631e+06 3.4289813993e+05 1.7397447582e+06 -1.1868827654e+03 -6.9411337628e+03 -3.0827203261e+03
210471.000000 -6.5248597456e+06 2.7346571276e+05 1.7088239715e+06 -1.1023516977e+03 -6.9449687875e+03 -3.1054792742e+03
210481.000000 -6.5355027526e+06 2.0399742525e+05 1.6776738978e+06 -1.0177694508e+03 -6.9479690501e+03 -3.1274799271e+03
210491.000000 -6.5452985535e+06 1.3450429068e+05 1.6463055385e+06 -9.3304505269e+02 -6.9500932517e+03 -3.1490159138e+03
210501.000000 -6.5542453449e+06 6.4993703649e+04 1.6147232695e+06 -8.4826316959e+02 -6.9513265320e+03 -3.1701200777e+03
210511.000000 -6.5623423718e+06 -4.5268608267e+03 1.5829303414e+06 -7.6333177493e+02 -6.9516724565e+03 -3.1908399990e+03
210521.000000 -6.5695881706e+06 -7.4044294803e+04 1.5509317554e+06 -6.7831700455e+02 -6.9511153857e+03 -3.2111596167e+03
210531.000000 -6.5759839976e+06 -1.4355817912e+05 1.5187351359e+06 -5.9331435614e+02 -6.9500035049e+03 -3.2307745568e+03
210542.000000 -6.5820376372e+06 -2.1999210170e+05 1.4830692749e+06 -4.9963065505e+02 -6.9474681529e+03 -3.2521474760e+03
210552.000000 -6.5866531135e+06 -2.8945201535e+05 1.4504592474e+06 -4.1433836555e+02 -6.9440433013e+03 -3.2711611550e+03
210562.000000 -6.5904104974e+06 -3.5887258930e+05 1.4176651910e+06 -3.2888363109e+02 -6.9396524018e+03 -3.2897132803e+03
210572.000000 -6.5933093166e+06 -4.2824577469e+05 1.3846839812e+06 -2.4350738687e+02 -6.9344515243e+03 -3.3078491074e+03
210582.000000 -6.5953521477e+06 -4.9756160595e+05 1.3515236173e+06 -1.5805732614e+02 -6.9283515511e+03 -3.3255534079e+03
210592.000000 -6.5965394364e+06 -5.6681482049e+05 1.3181885994e+06 -7.2434488623e+01 -6.9213751218e+03 -3.3428862367e+03
210602.000000 -6.5968692488e+06 -6.3599084078e+05 1.2846799286e+06 1.3132681093e+01 -6.9135371391e+03 -3.3597760184e+03
210612.000000 -6.5963421949e+06 -7.0508609546e+05 1.2510059800e+06 9.8664842500e+01 -6.9047992229e+03 -3.3762415371e+03
210622.000000 -6.5949578250e+06 -7.7409072045e+05 1.2171696291e+06 1.8422893053e+02 -6.8952148223e+03 -3.3922632329e+03
210632.000000 -6.5927172845e+06 -8.4299477392e+05 1.1831728757e+06 2.6972220726e+02 -6.8847722257e+03 -3.4078667026e+03
210642.000000 -6.5896217468e+06 -9.1179043947e+05 1.1490213447e+06 3.5515780257e+02 -6.8734399550e+03 -3.4230278559e+03
210652.000000 -6.5856730178e+06 -9.8046947794e+05 1.1147222857e+06 4.4051969879e+02 -6.8612481179e+03 -3.4377344982e+03
210663.000000 -6.5803408919e+06 -1.0558695980e+06 1.0768274107e+06 5.3442272527e+02 -6.8467851022e+03 -3.4533853547e+03
```

Figure 3.6. ConvertTool Output File.

4. Edit Propagated Data File

The propagated data file required much less manipulation. A Fortran program, "edtprop," was used to add the header for convertTool, convert the input file times to MET in seconds and convert the data from English units to metric units. A copy of the program is in Appendix A. ConvertTool was then used to transform the file from M50 coordinates to J2000 coordinates. Finally, the file of over 16,000 state vectors was hand edited to break it up by flight day.

5. Create STK Vehicle Files

STK Vehicle files for each flight day were created using the Shuttle STK vehicle library file as a guide. A vehicle file was created for each day from each data source. GPS ephemeris data and the propagated file ephemeris data were each inserted into a model Shuttle vehicle file in ECI J2000 coordinates. A scenario was created for every flight day which included a vehicle generated from GPS ephemeris data and one generated from the propagated ephemeris data. An example vehicle file is shown in Appendix C. The scenarios were animated so that both vehicles could be viewed simultaneously to better visualize the similarities and differences between the tracks.

6. Matlab Comparison

Matlab was employed for a detailed comparison of the GPS and propagated data files for each day. The Matlab M-file, "diffday#.m" was executed to plot J2000 XYZ position and velocity vector components and the position and velocity vector magnitudes for both data sets. A plot of the data points in three dimensions was also obtained using "orbplt#.m" to assist in visualizing the orbit that was generated by the GPS data. Appendices D and E contain examples of these M-files.

Since the propagated data and GPS data could not be compared point for point, it was difficult to obtain hard numbers for comparison of GPS and reference track data. In an effort to match the data sets point for point, the process of editing the GPS data files

for days 251 and 252 was repeated with the exception of thinning the data by a factor of ten. The NAVG-11 file was hand edited to remove headers and unnecessary columns, and then run through the stream editor to remove colons. The Fortran program "edtsv" shown in Appendix B was then executed to convert state vector times to MET and English units to metric units. ConvertTool was invoked to transform the file from M50 coordinates to J2000 coordinates. GPS and NAVG-11 state vectors were then hand matched for days 251 and 252. A Matlab M-file was used to compare position and velocity vector components, position and velocity vector magnitudes, and Root Mean Square (RMS) differences between the GPS data and the NAVG-11 data. A copy of the Matlab script "diffmat#.m" is shown is Appendix F.

IV. RESULTS

GPS data was available for every flight day of STS-69; however, GPS data was not available for the entire duration of each flight day. The percentage of each day for which GPS data was available for comparison with the propagated data varied greatly from day to day. Day 258 was covered most sparsely by GPS with data being available only 12 pecent of the day. In contrast, GPS data was available for 93 percent of day 255. The average percentage of the day during the mission for which GPS data was available was 65 percent. These results are shown in Figure 4.1.

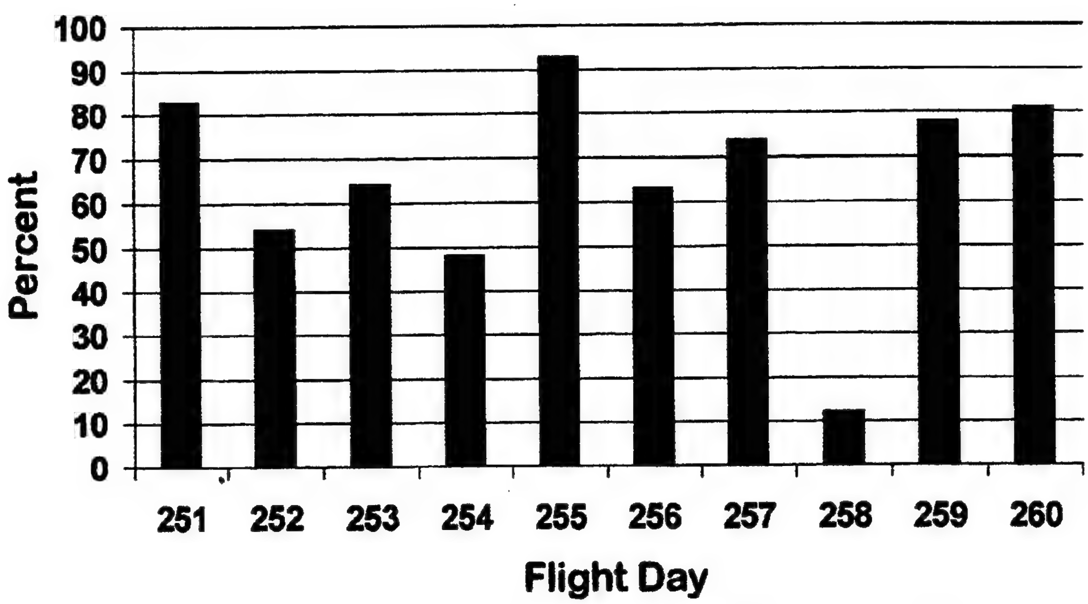


Figure 4.1. Percentage of each day for which GPS data was available.

A. MATLAB COMPARISON RESULTS

1. Day 251

Day 251 data was typical of the results achieved during the mission. Figure 4.2 at the end of the section displays how dense the GPS data is relative to the propagated file reference track. Of note is the fact that the GPS data, displayed as asterisks, has already

been thinned by a factor of ten. The propagated file is derived from the original state vectors which come from several sources as shown in Figure 4.3. The sources displayed trends when compared with the GPS data, and these trends appeared to be diurnal in some cases. The list of tracking source identifiers is shown in Table 4.1.

Source	**Identifier**
East TDRS	ESTR
West TDRS	WSTR
Ascension Island	ASCC
Bermuda	BDQC
Kwajalein Island	KMTC
Wallops Island	WLRC

Table 4.1. NASA Shuttle Tracking Sources.

A plot of the position vector XYZ components in J2000 coordinates for day 251 shown in Figure 4.4 indicates that the GPS data represented by the heavy line follows very closely with the reference track represented by the thinner line. A two hour gap in GPS data is seen. This is typical of the gaps in GPS data that were observed every day. A plot of the velocity vector in XYZ components in J2000 coordinates in Figure 4.5 also shows this gap in GPS data and some spurious GPS data points. Both plots display sinusoidal patterns for each of the components which are associated with an inclined circular orbit.

The position vector magnitude is equivalent to the spacecraft's distance from the center of the Earth, or radius of its orbit, as shown in figure 4.6. Plotting of the position vector magnitude in Figure 4.7 shows that the radius is fairly constant as would be expected for the Shuttle's circular orbit. This plot of vehicle altitude was very effective in indicating when vehicle maneuvers occurred. The velocity vector magnitude plot also indicates that the velocity vector was quite constant as was expected for a circular orbit. Both the position and velocity vector magnitude plots show that spurious GPS data points were present.

The three dimensional plot of the GPS data for day 251 in J2000 coordinates shown in Figure 4.8 displays how well the GPS data captured the Shuttle's circular orbit. The fact that the orbit is inclined, and that the GPS data is extremely dense is reflected in this plot. Erroneous data points are also visible.

Point for point comparison of the GPS position vector magnitudes with the NAVG-11 position vector magnitudes in Figure 4.9 shows an altitude difference of ± 150 m. Figure 4.10 shows that the velocity vector magnitude difference between the two data sets was generally $\pm$ 1 m/s and did not exceed 4 m/s. The RMS position difference between the GPS data and NAVG-11 data displayed in Figure 4.11 was primarily between 1400 and 1550 m, and the RMS velocity difference displayed in Figure 4.12 did not exceed 9 m/s.

2. Typical Data

The position and velocity vector magnitude plots for day 252 shown in Figure 4.13 display a sinusoidal pattern associated with what appears to be an elliptical orbit. Closer examination of the position vector magnitude plot scale shows that the peak to peak difference associated with apogee and perigee is approximately 5000 meters. Gaps in GPS data and spurious data points are also experienced. Day 255 position and velocity vector magnitude plots displayed in Figure 4.14 are similar to those for day 252; however, the errant data points are more severe.

GPS data for day 258 was very sparse with only 12 percent of the flight day covered by GPS data. The sparse amount of data allowed a detailed look at both data sets as shown in Figure 4.15 and displayed the imperfect nature of an actual vehicle orbiting the Earth. Although there were a few spurious data points, the GPS data followed the reference track so closely that it was difficult to discern the GPS data from the reference track.

3. Maneuvers

The position vector magnitude plot proved extremely useful in detecting Shuttle maneuvers. The day 253 position vector magnitude plot shown in Figure 4.16 displays a gap in GPS data just prior to the maneuver. A small gap in GPS data is experienced at the beginning of the maneuver which involves an altitude change of 10,000 m; however, the GPS track follows the reference track through the rest of the maneuver. Figure 4.17 also displays an example of GPS tracking through a maneuver. This maneuver is more severe involving a change in altitude of 60,000 m. A loss of GPS data is experienced in the middle of the maneuver with GPS data being reacquired before completion of the maneuver.

4. Errant GPS Data

There are several examples of errant GPS data over the course of the eleven flight days of STS-69. One of the best examples occurs on day 250 and is shown in Figure 4.18 and Figure 4.19. Figure 4.18 is a three dimensional plot of the GPS data for day 250. This plot shows a segment of GPS data that fails to conform to the Shuttle's circular orbit. This period of bad data can be clearly identified in the position vector component plot shown in Figure 4.19. At the start of the day's data the GPS data does not follow the reference track. After a period of approximately 1300 seconds, the GPS data changes drastically and matches the reference track.

GPS data for day 259 has an interesting anomaly that is exhibited in the position vector magnitude plot in Figure 4.20. A segment of GPS data appears to be disjointed from the rest of the data. In the three dimensional plot of Figure 4.21 this period of errant data appears as a separate orbit at a different inclination. Several spurious data points are also present, particularly in the velocity vector magnitude plot.

The position and velocity vector magnitude plots presented the most dramatic results of errant data. The Day 260 position and velocity vector magnitude plot in Figure 4.22 is an example of this observation. The last 5000 seconds of position and velocity data for the Day 260 GPS data varies significantly from the reference track. This variance

in the data includes as much as a 20 km difference in altitude and a 1.7 km/s difference in velocity.

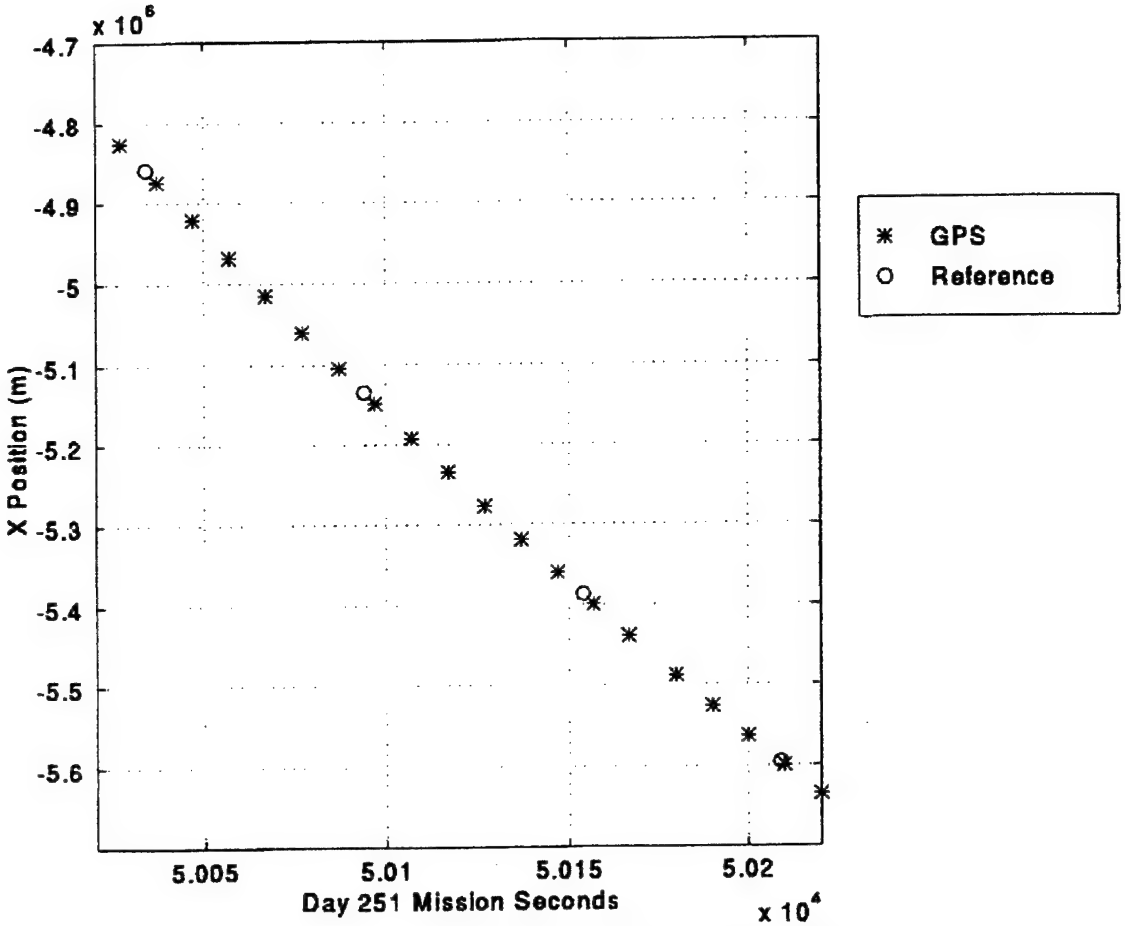


Figure 4.2. Density of GPS Data.

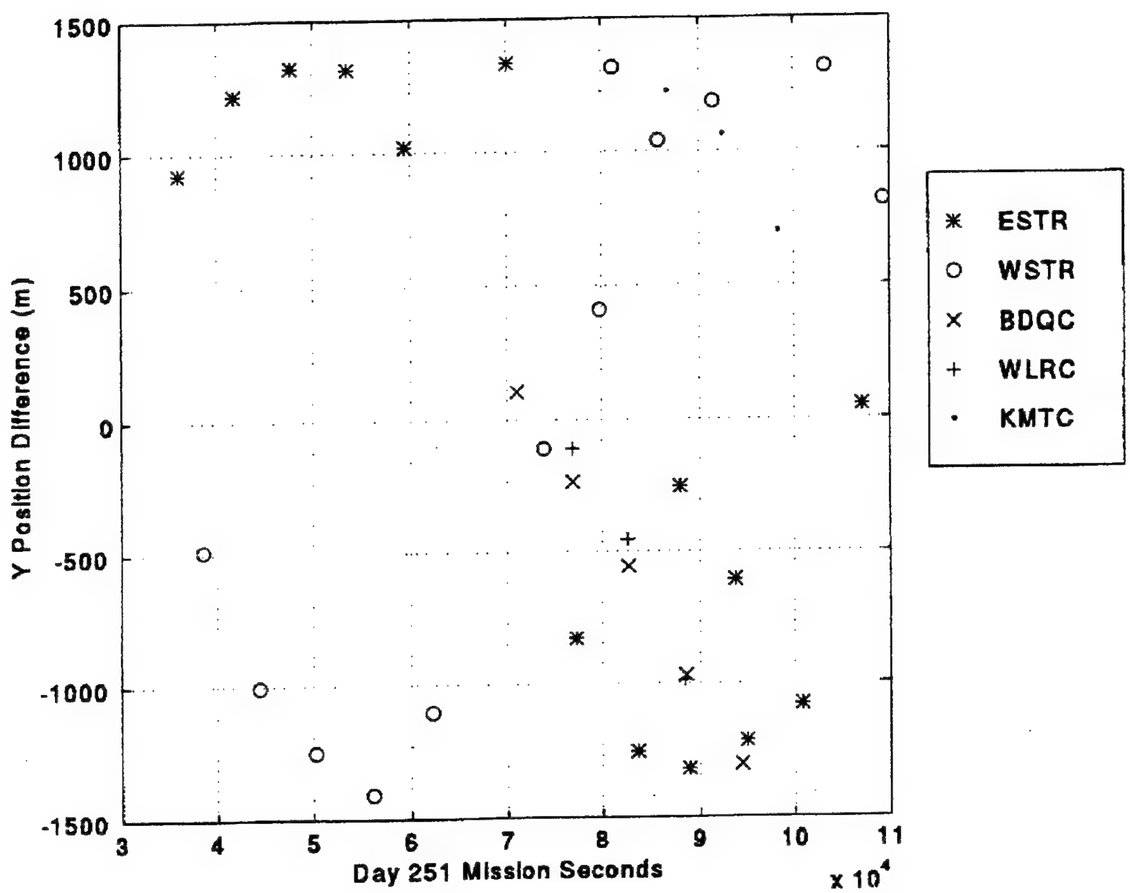


Figure 4.3. NAVG-11 Data Sources.

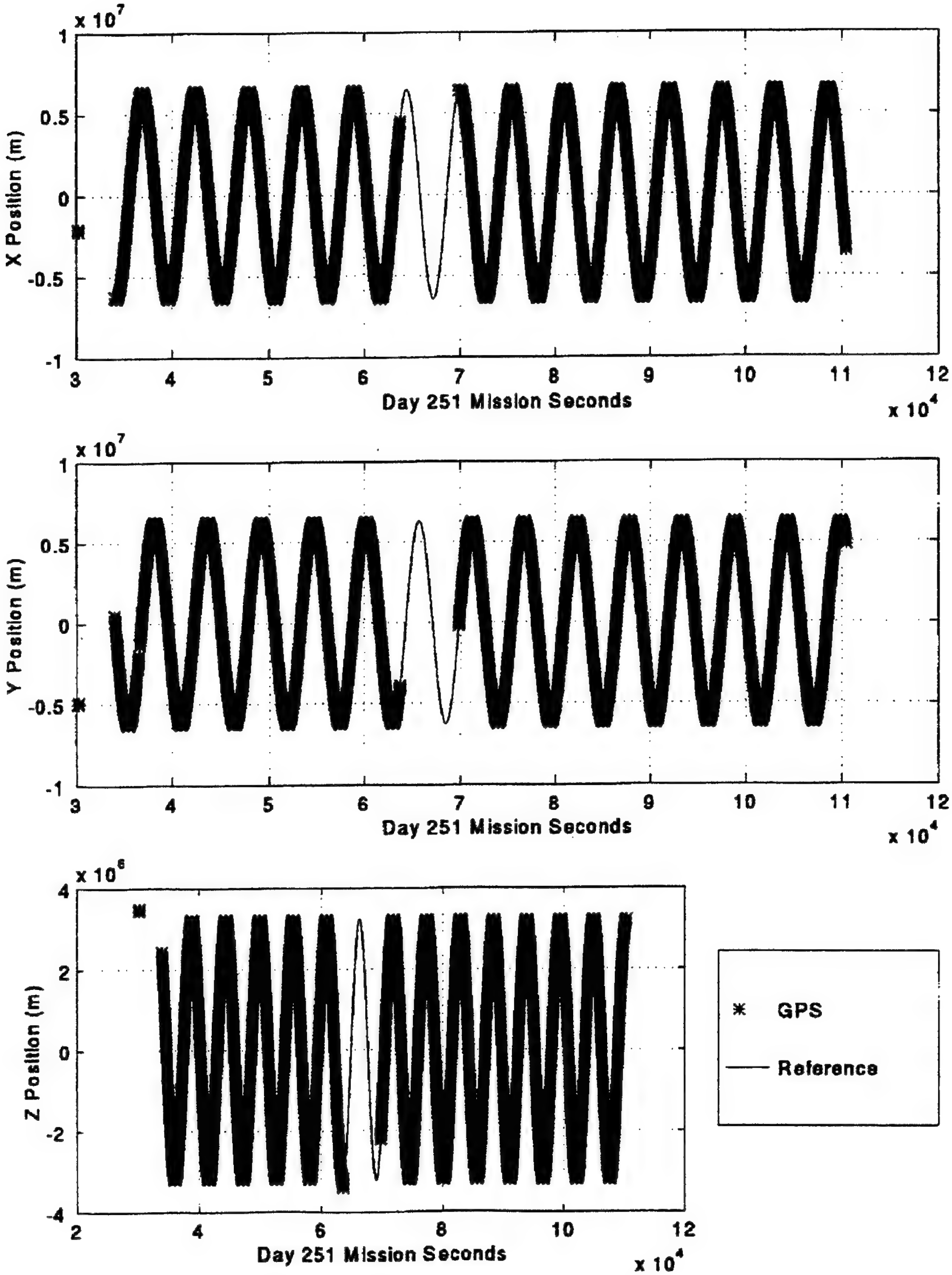


Figure 4.4. Day 251 Position Vector Components in J2000 Coordinates.

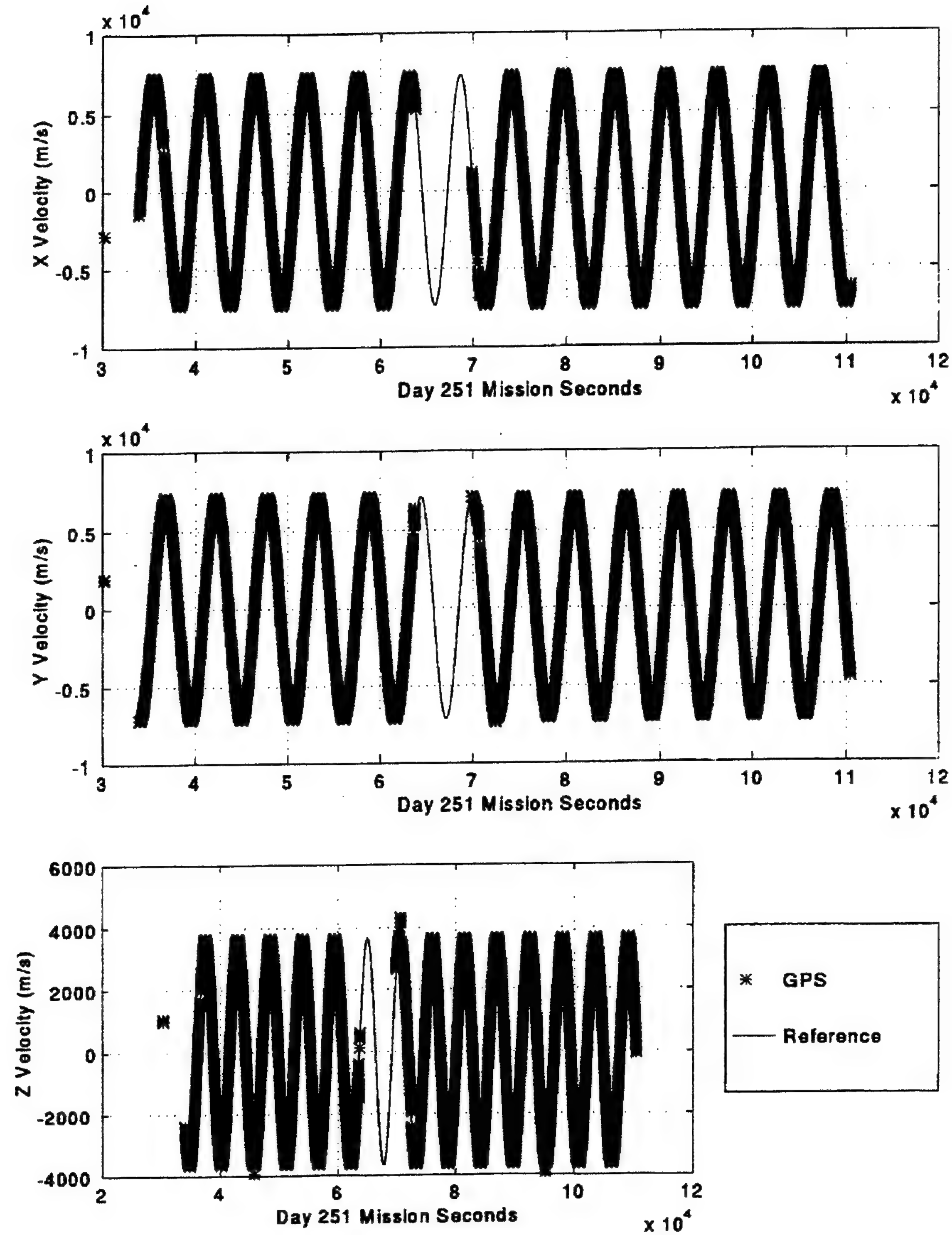


Figure 4.5. Day 251 Velocity Vector Components in J2000 Coordinates.

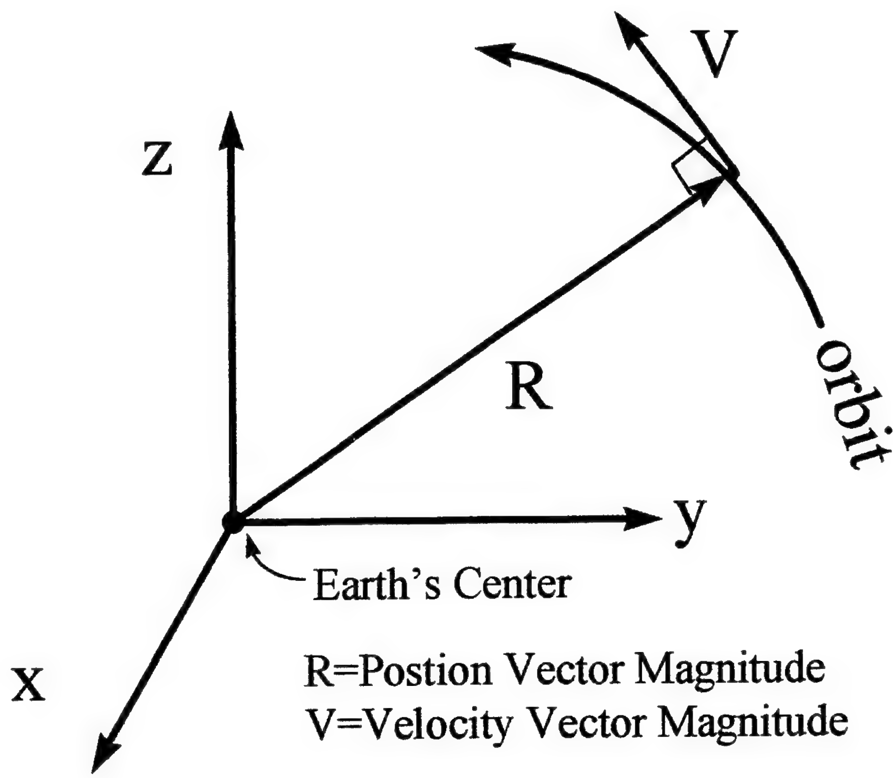
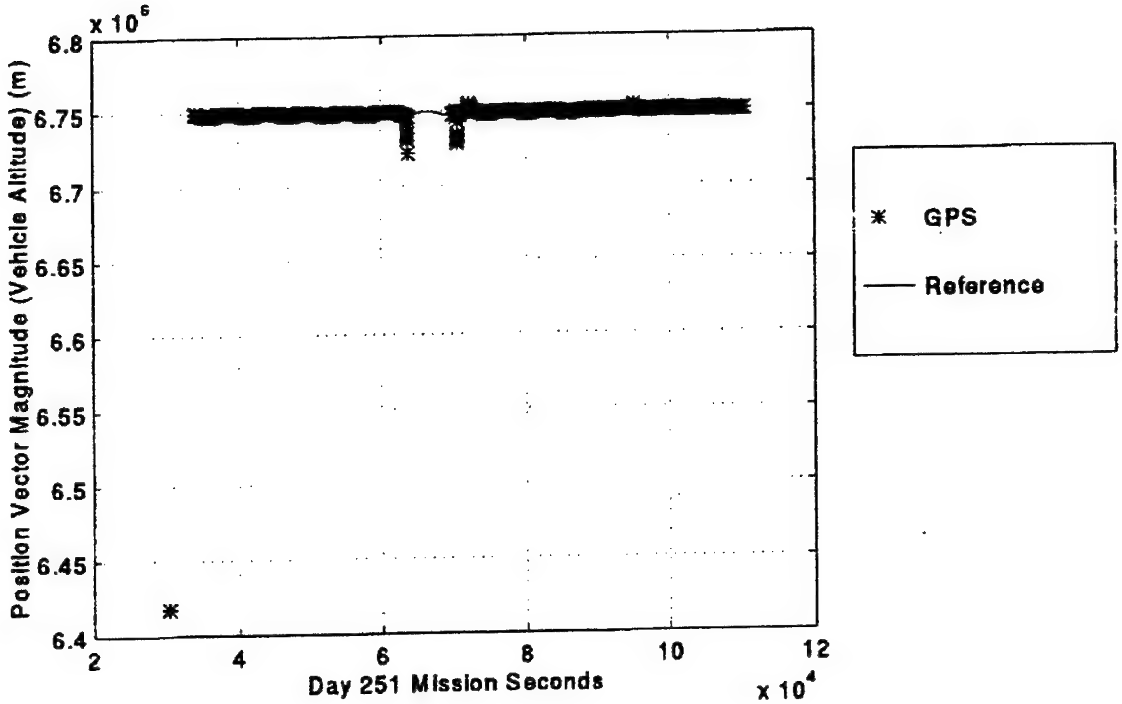


Figure 4.6. Position Vector Magnitude.



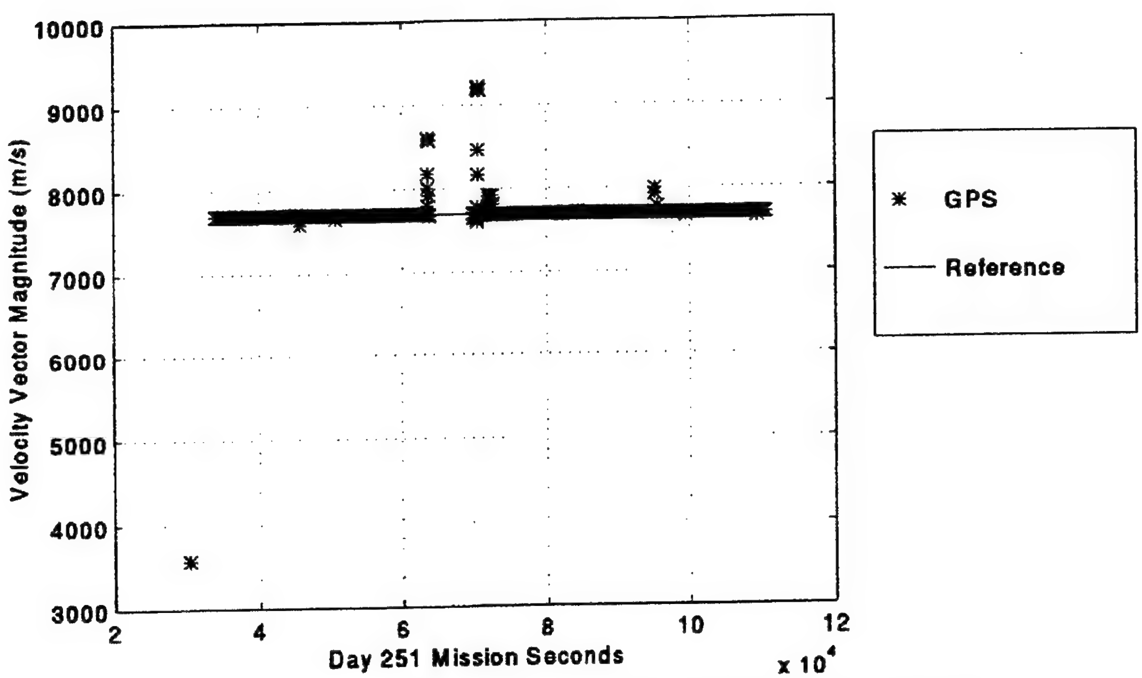


Figure 4.7. Day 251 Position and Velocity Vector Magnitude.

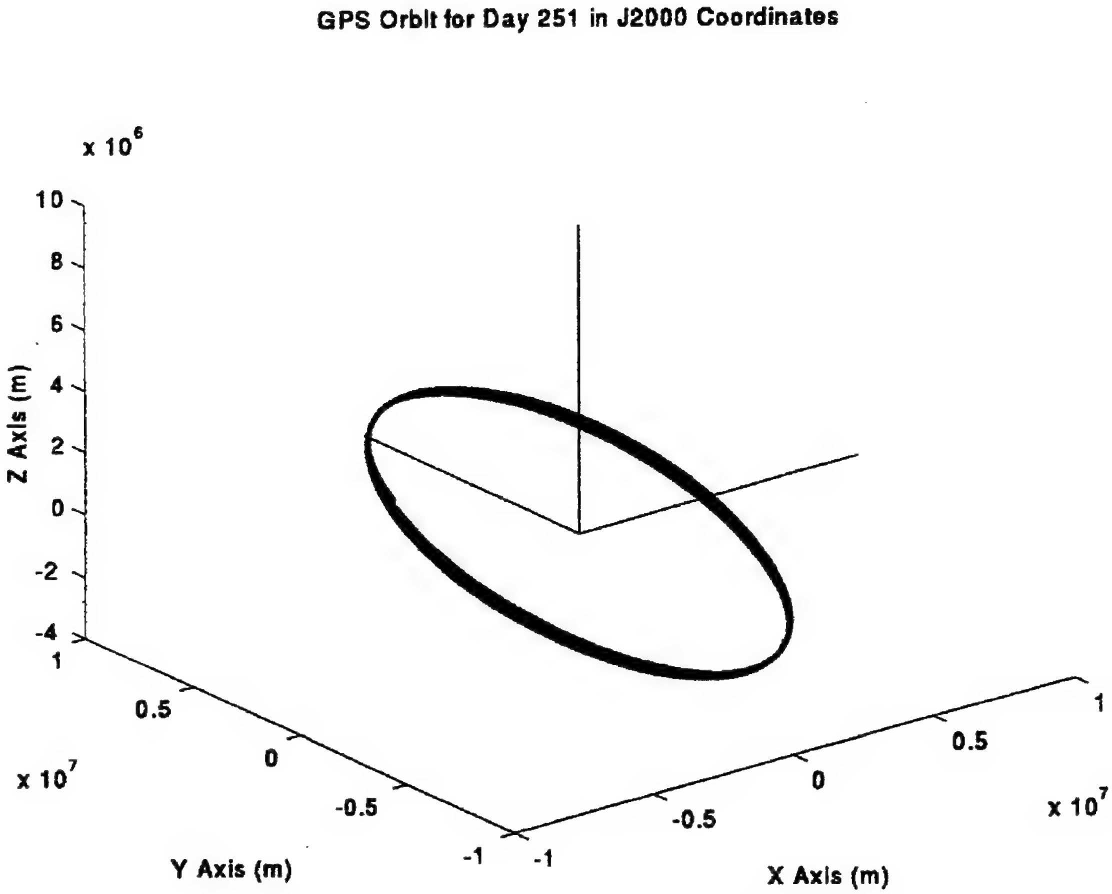


Figure 4.8. Day 251 GPS Orbit in J2000 Coordinates.

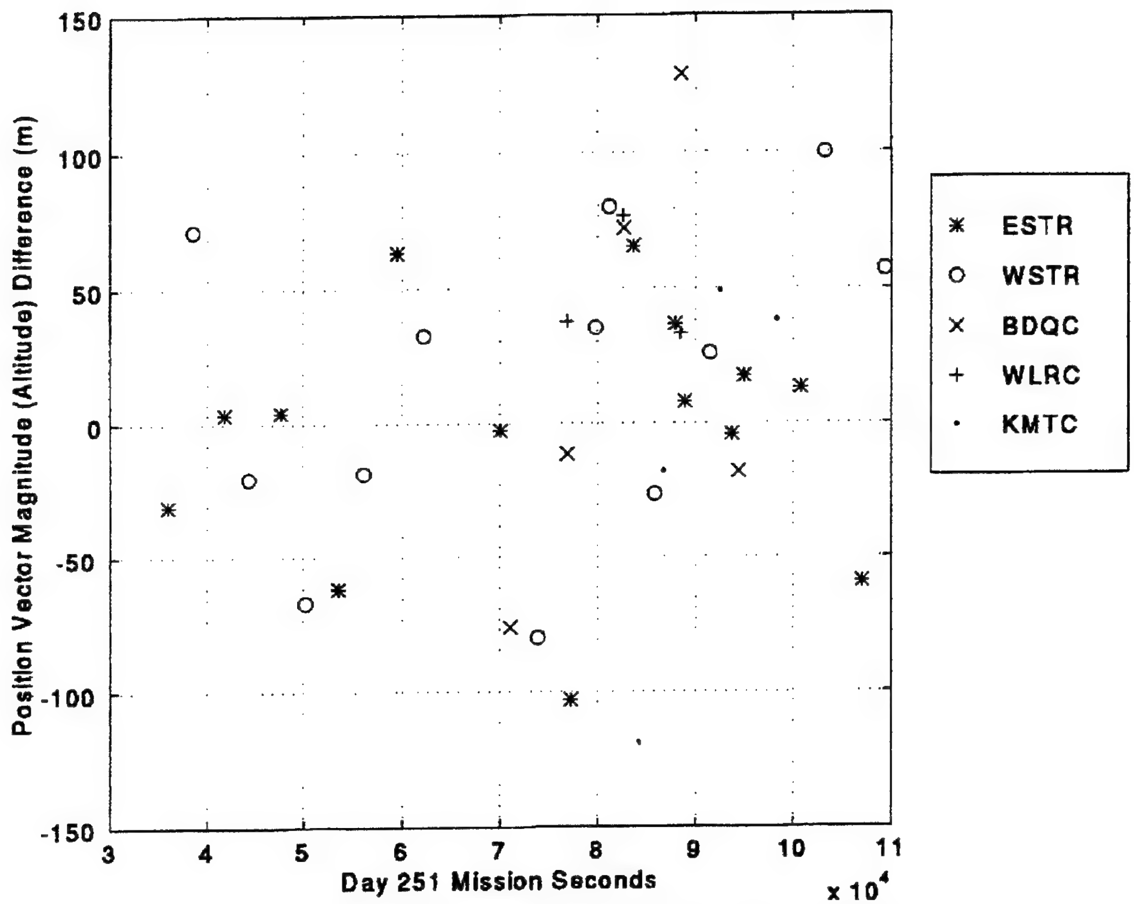


Figure 4.9. Day 251 Position Vector Magnitude Difference.

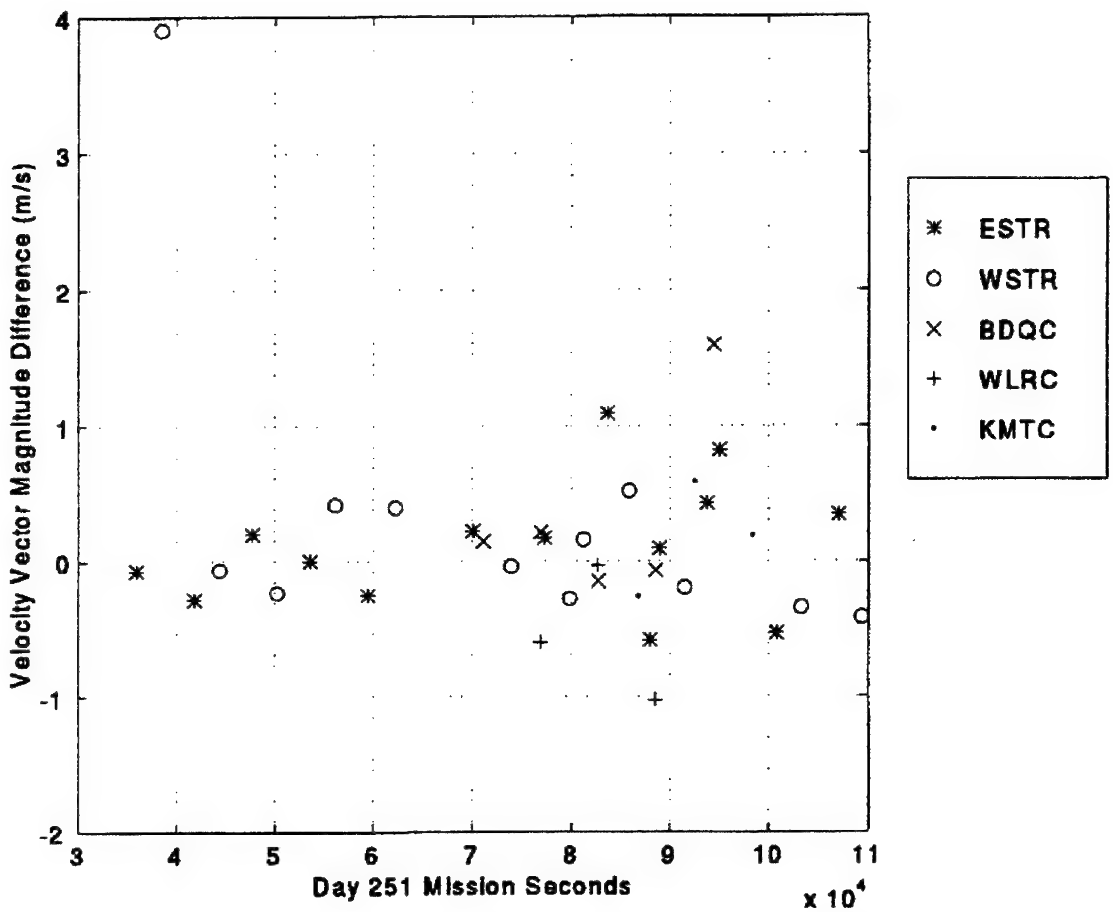


Figure 4.10. Day 251 Velocity Vector Magnitude Difference.

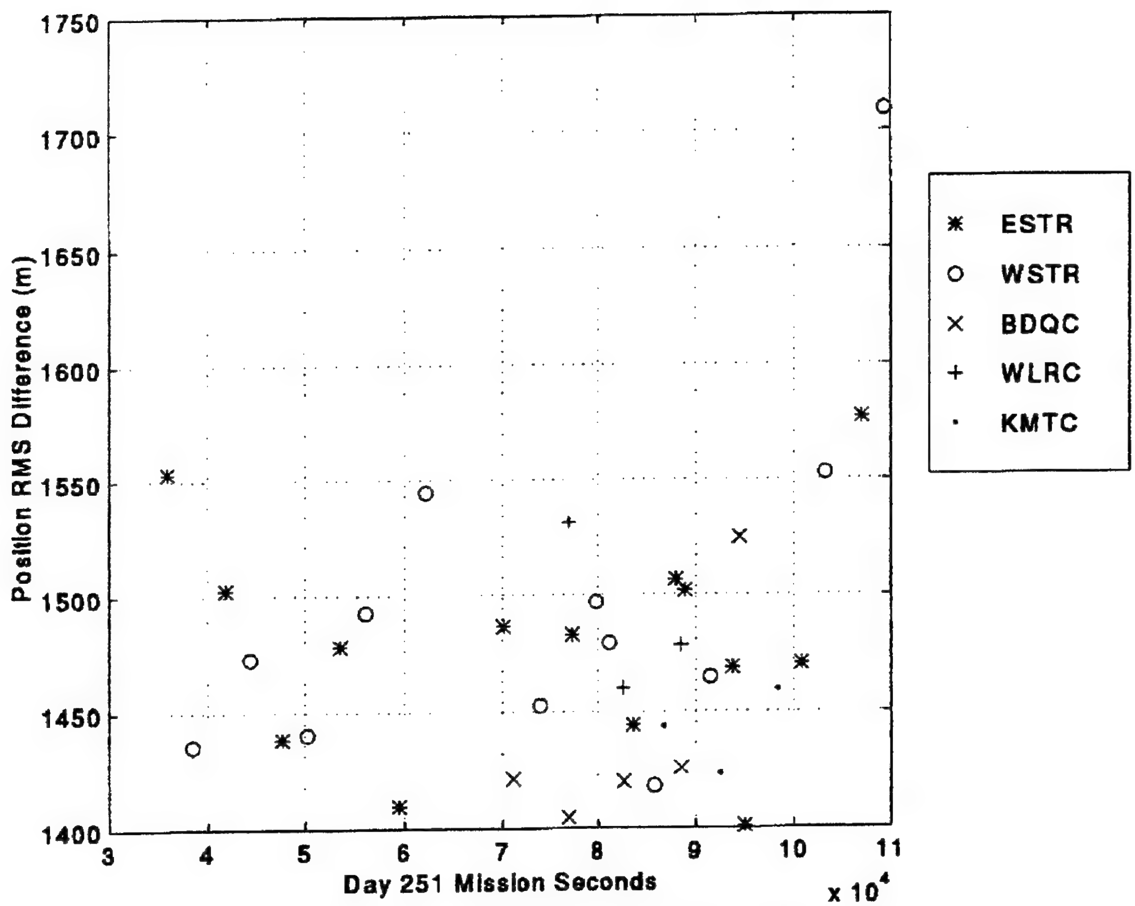


Figure 4.11. Day 251 Position RMS Difference.

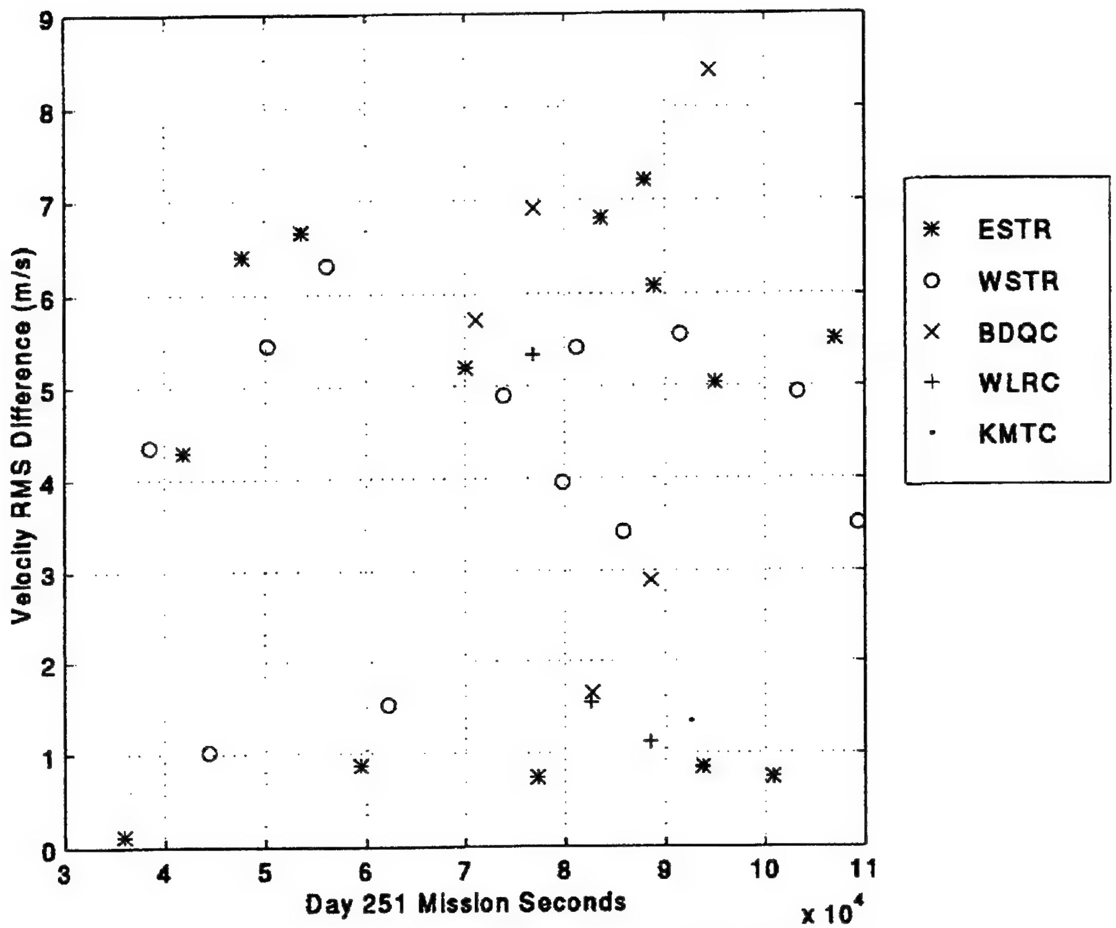
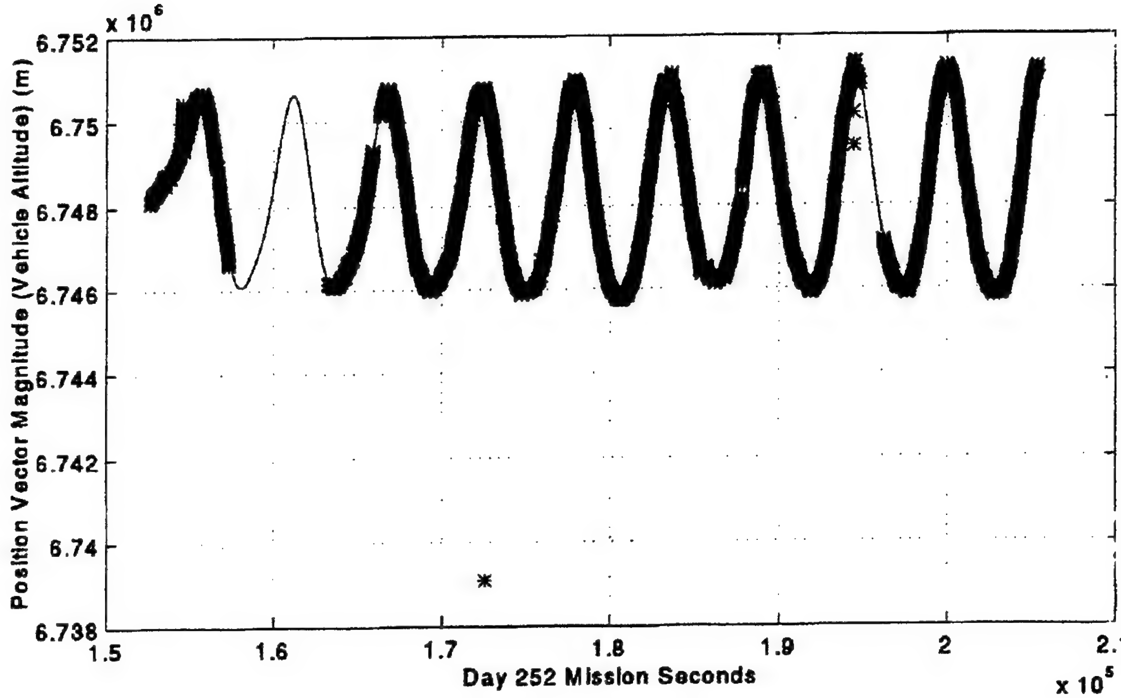


Figure 4.12. Day 251 Velocity RMS Difference.



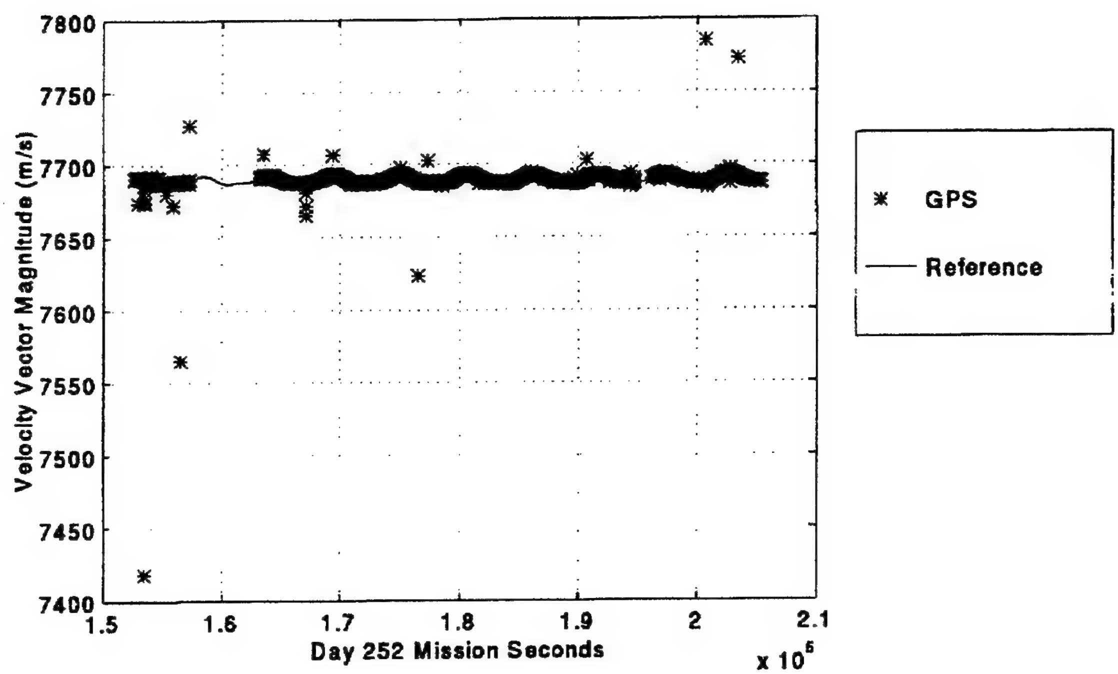


Figure 4.13. Day 252 Position and Velocity Vector Magnitude.

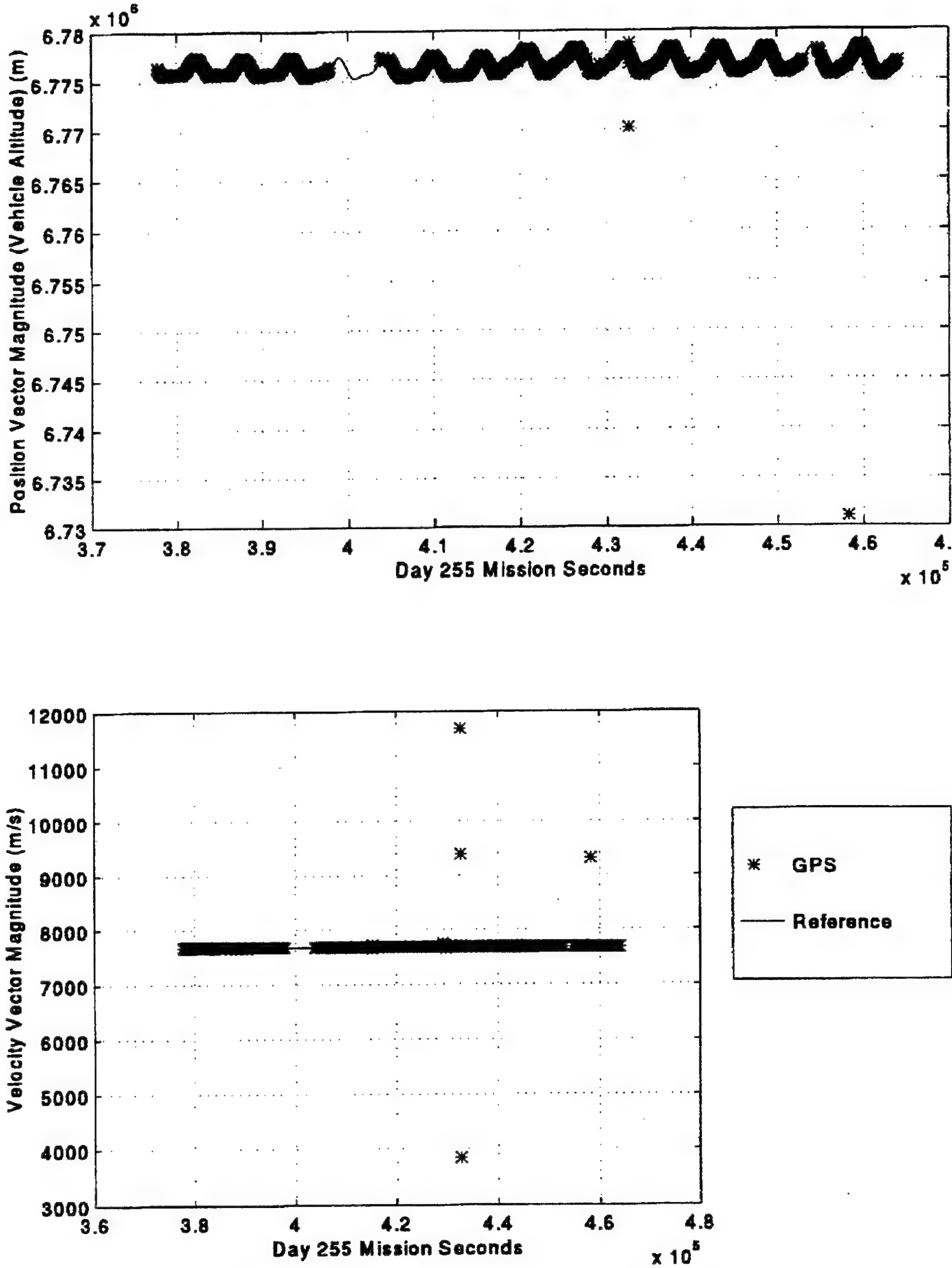
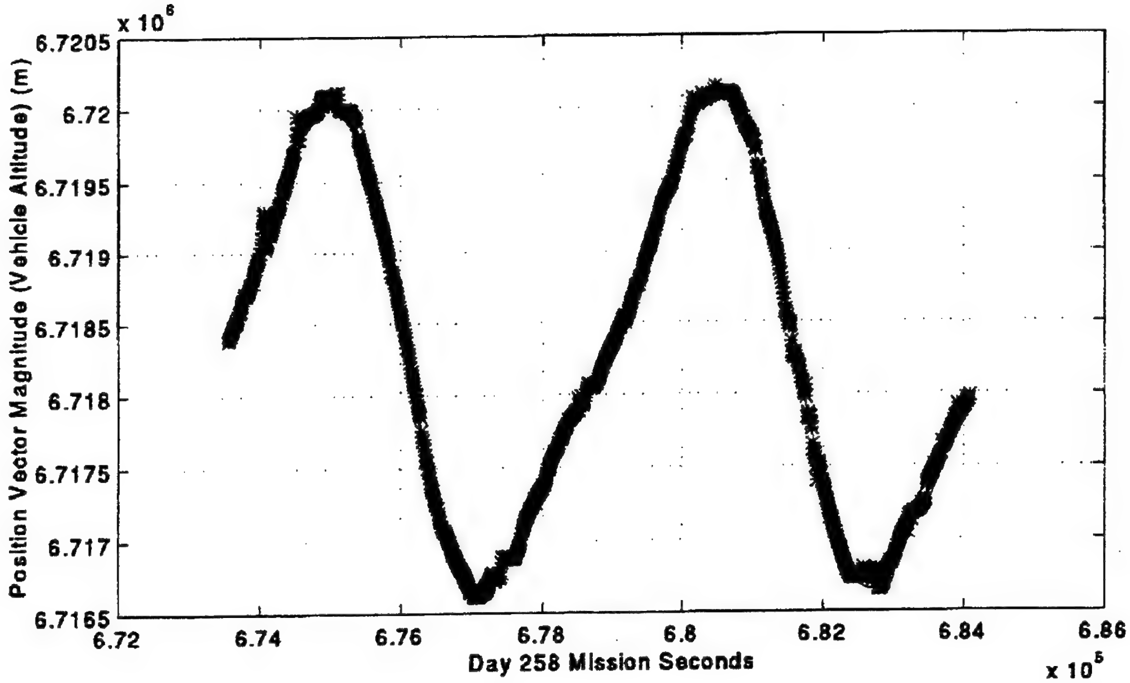


Figure 4.14. Day 255 Position and Velocity Vector Magnitude.



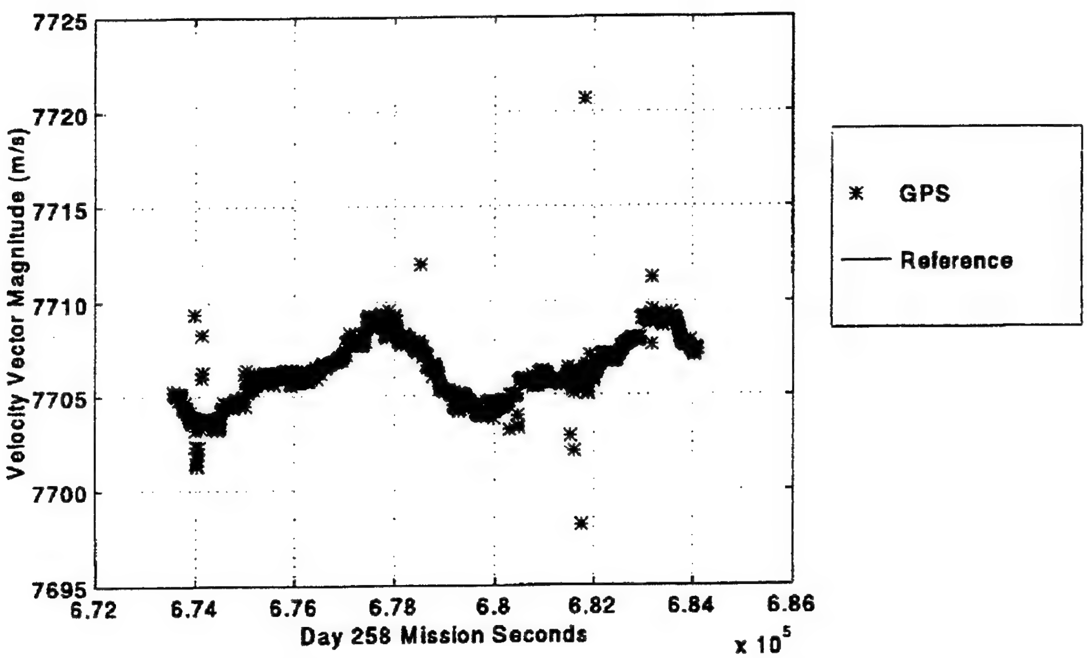


Figure 4.15. Day 258 Position and Velocity Vector Magnitude.

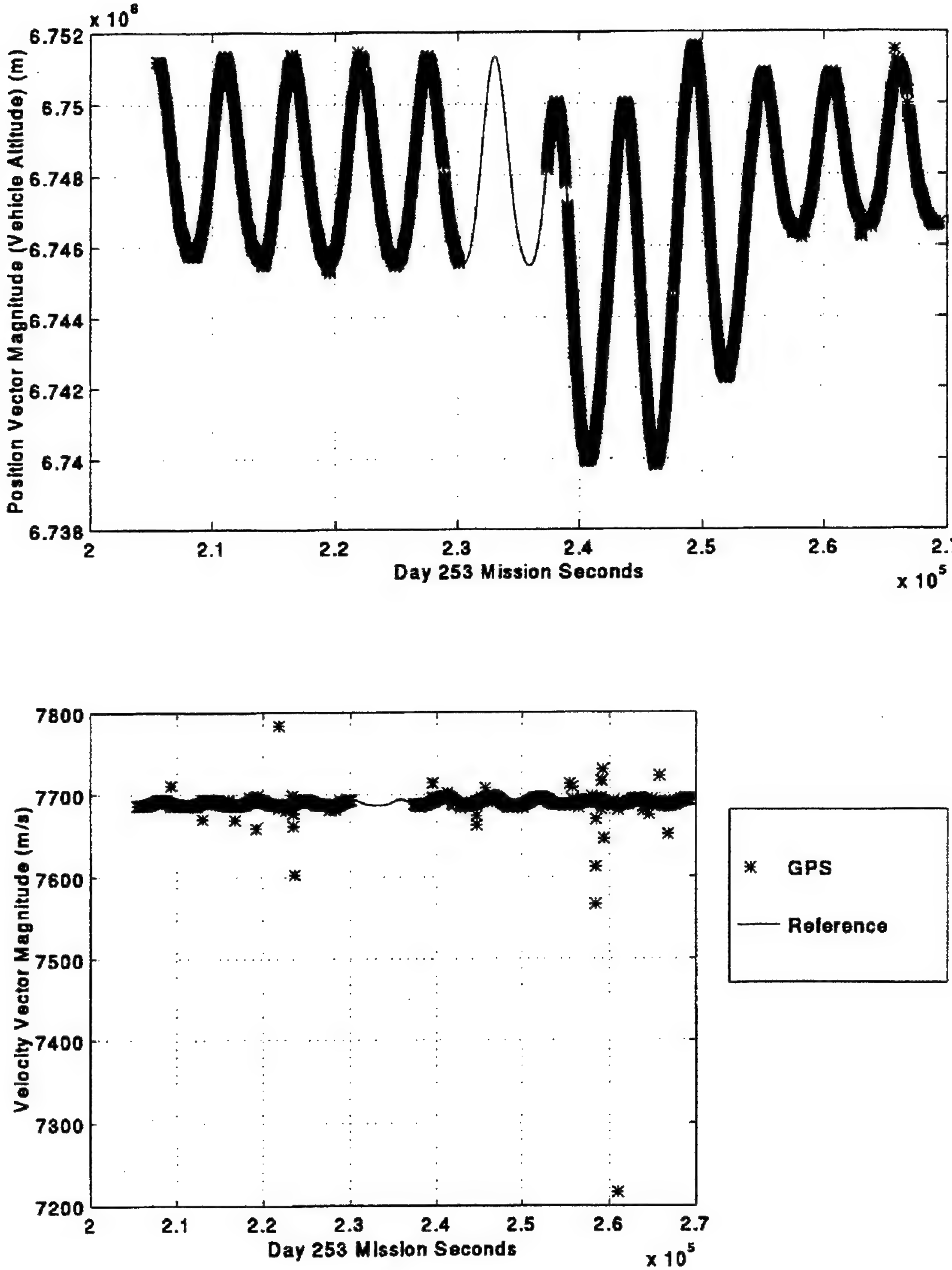


Figure 4.16. Day 253 Position and Velocity Vector Magnitude.

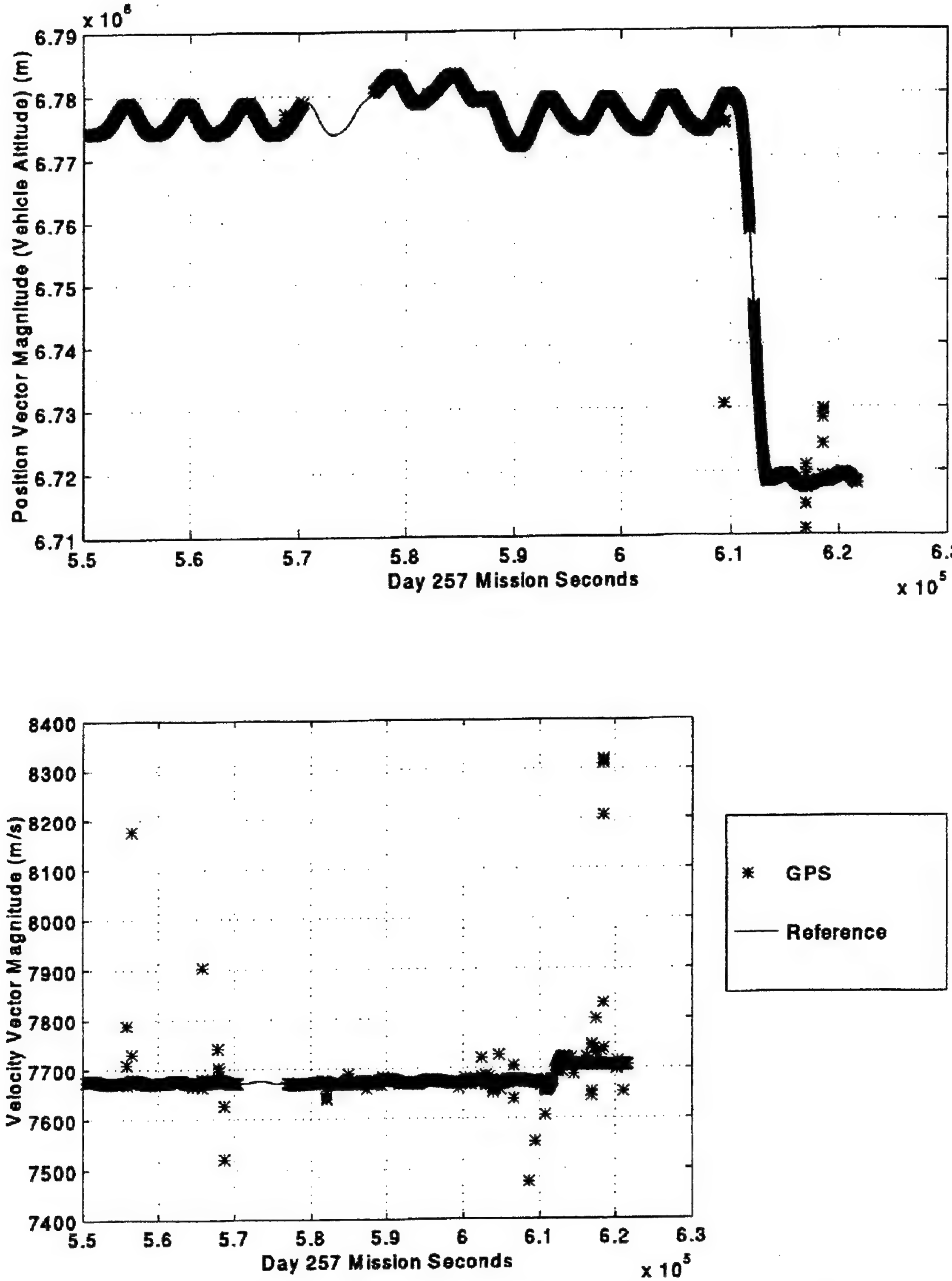


Figure 4.17. Day 257 Position and Velocity Vector Magnitude.

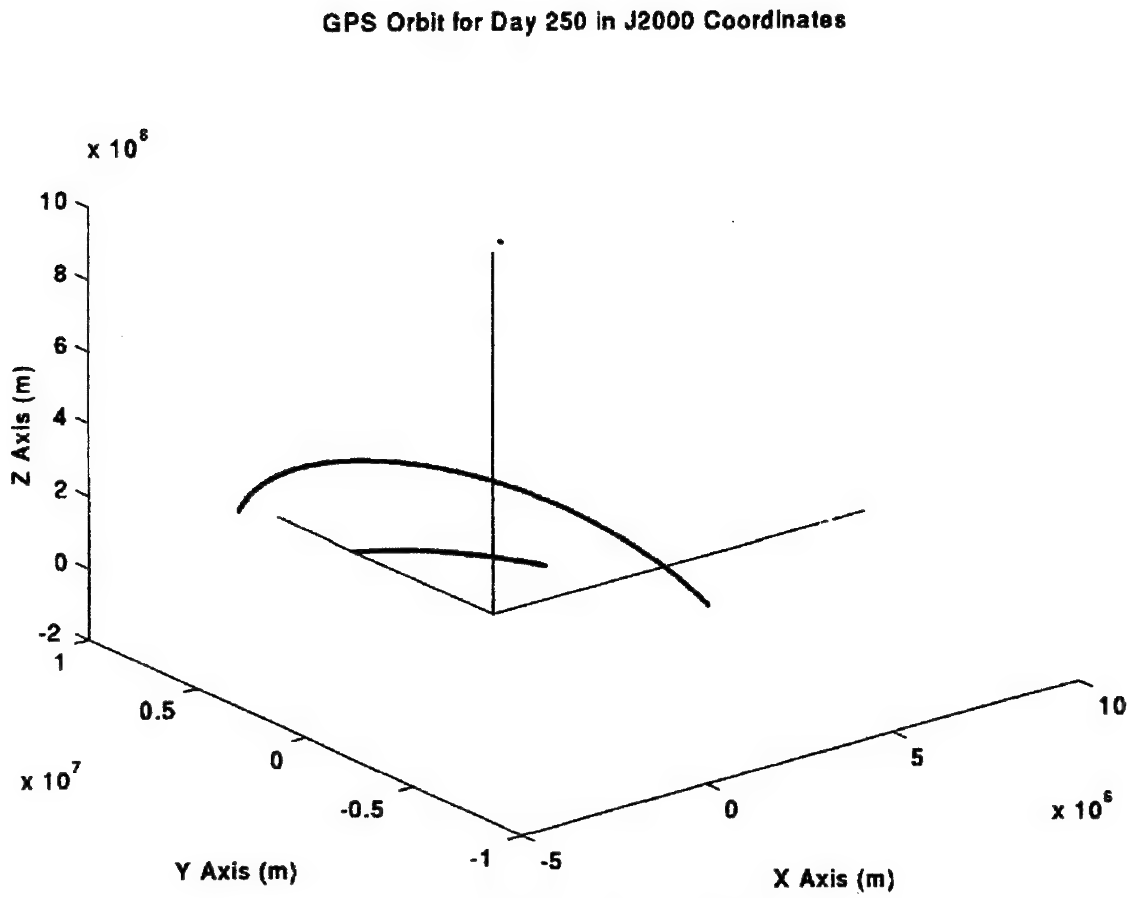


Figure 4.18. Day 250 GPS Orbit in J2000 Coordinates.

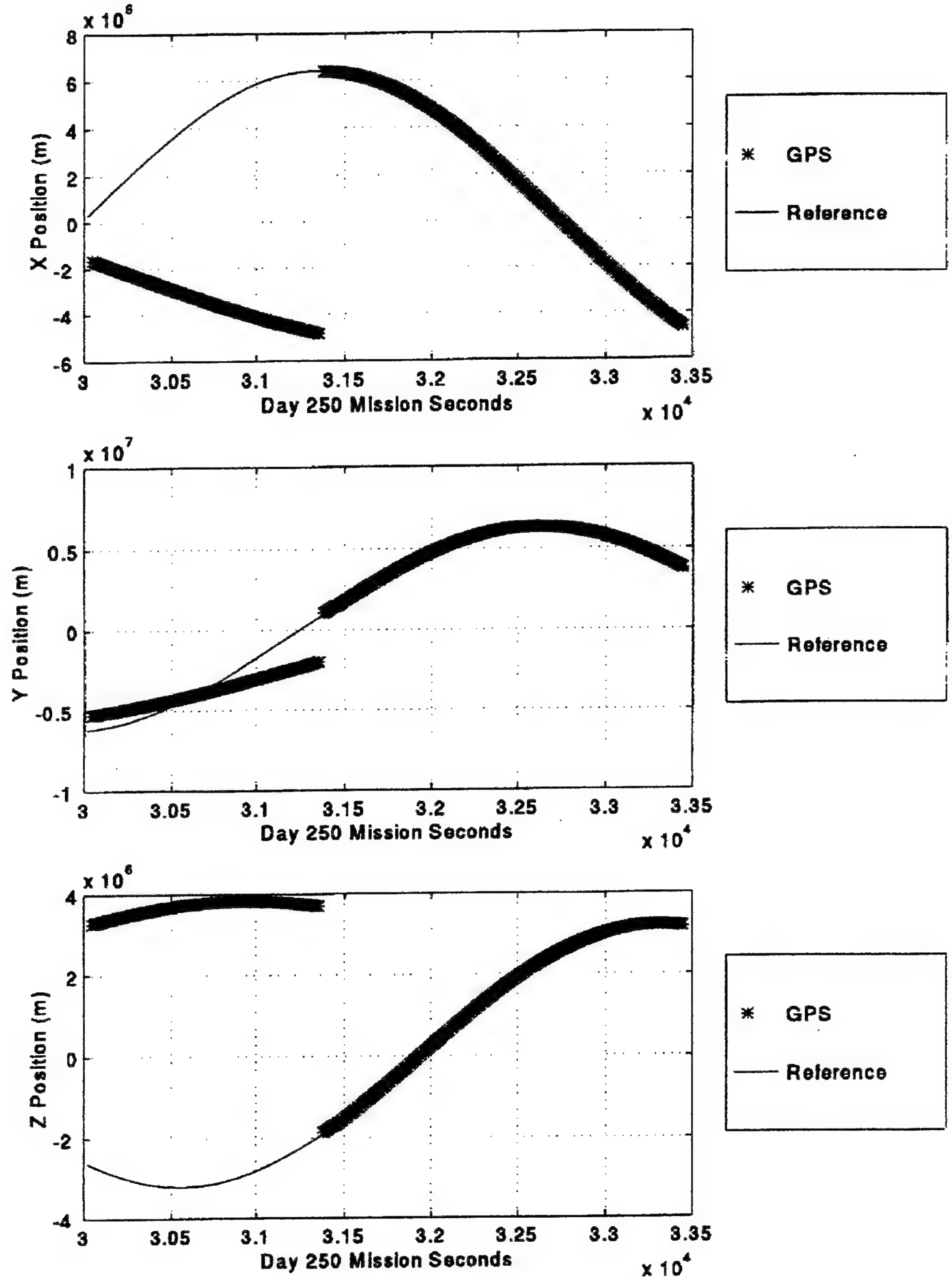


Figure 4.19. Day 250 Position and Velocity Vector Magnitude.

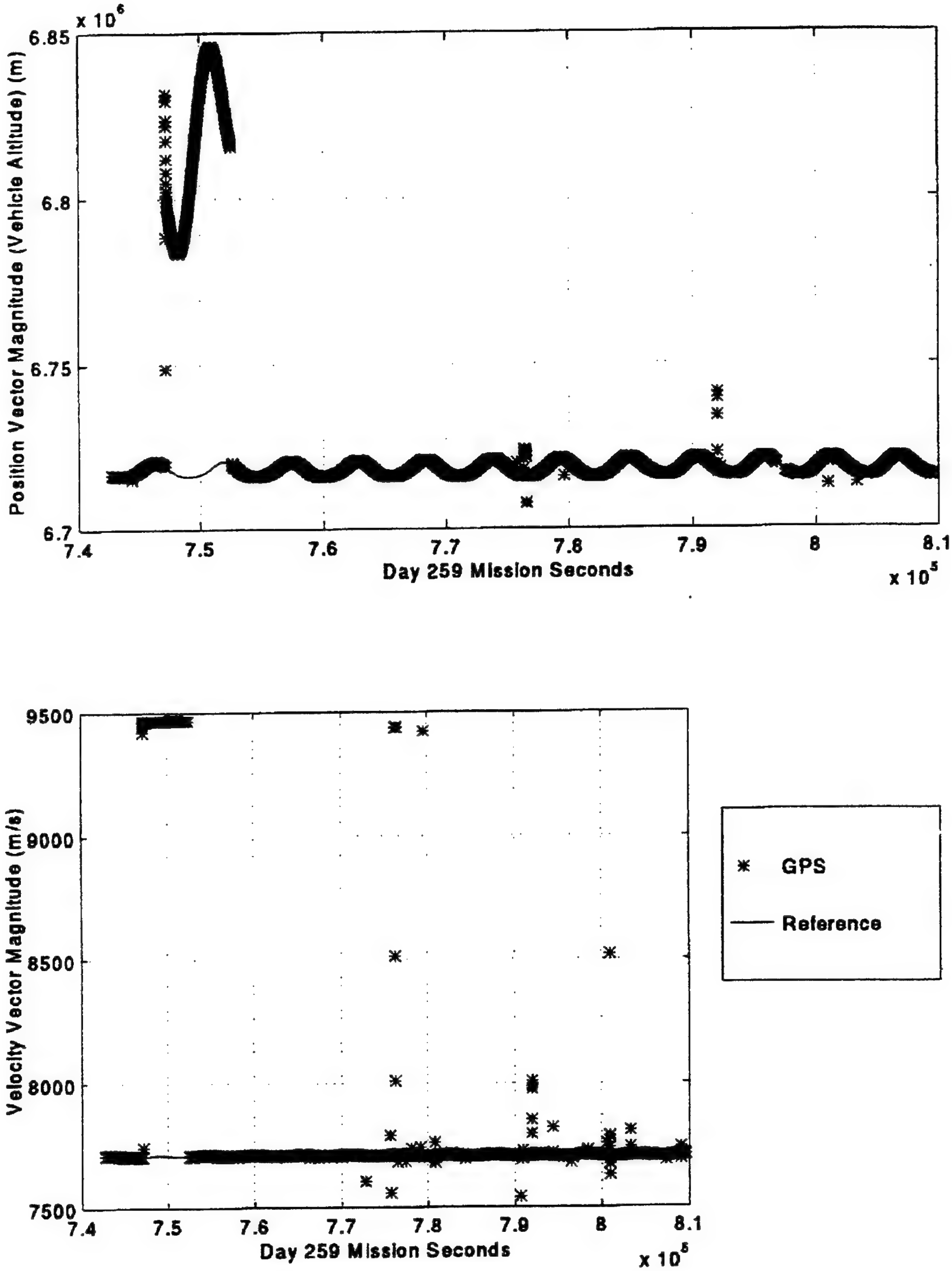


Figure 4.20. Day 259 Position and Velocity Vector Magnitude.

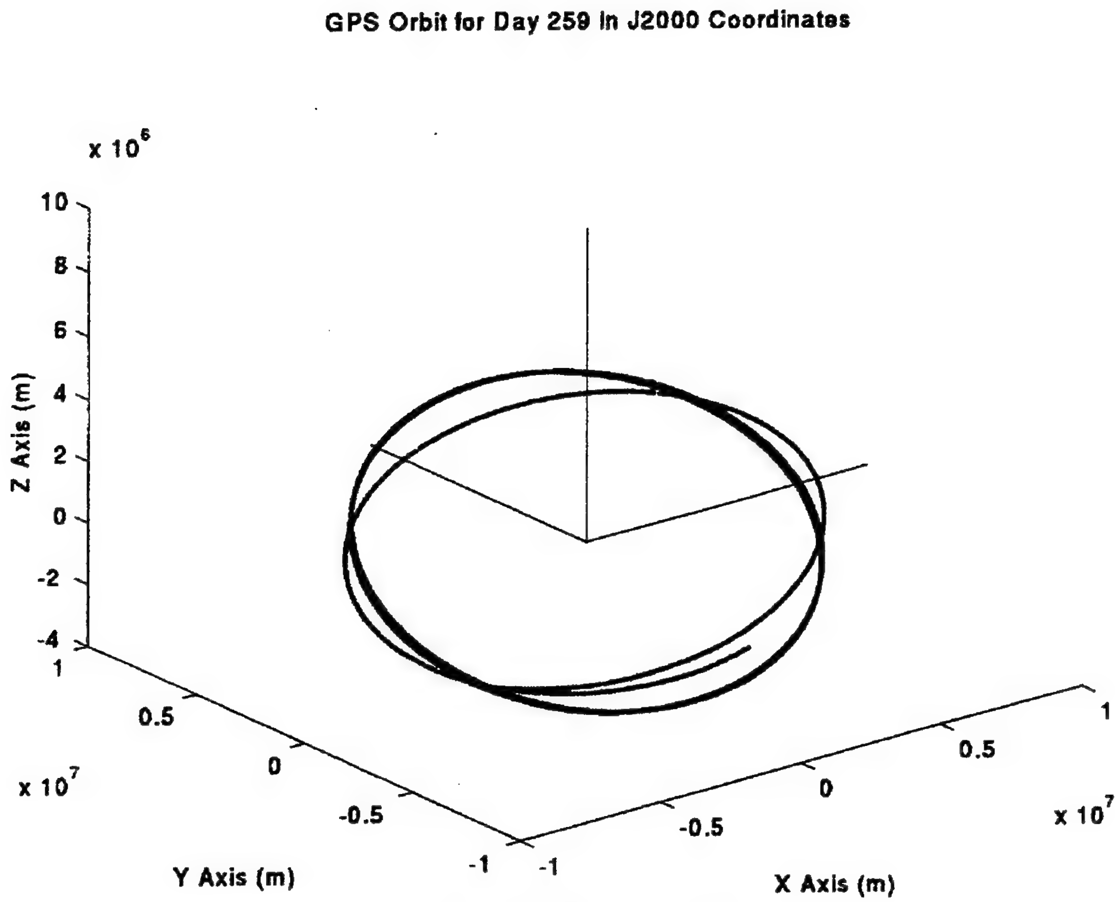
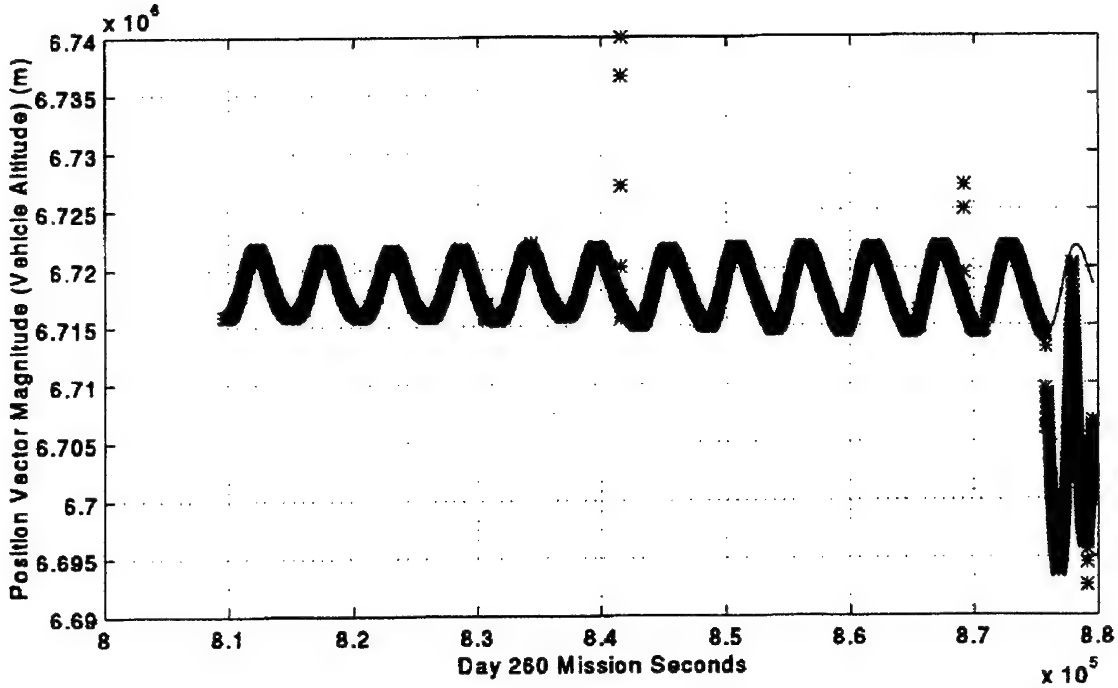


Figure 4.21. Day 259 GPS Orbit in J2000 Coordinates.



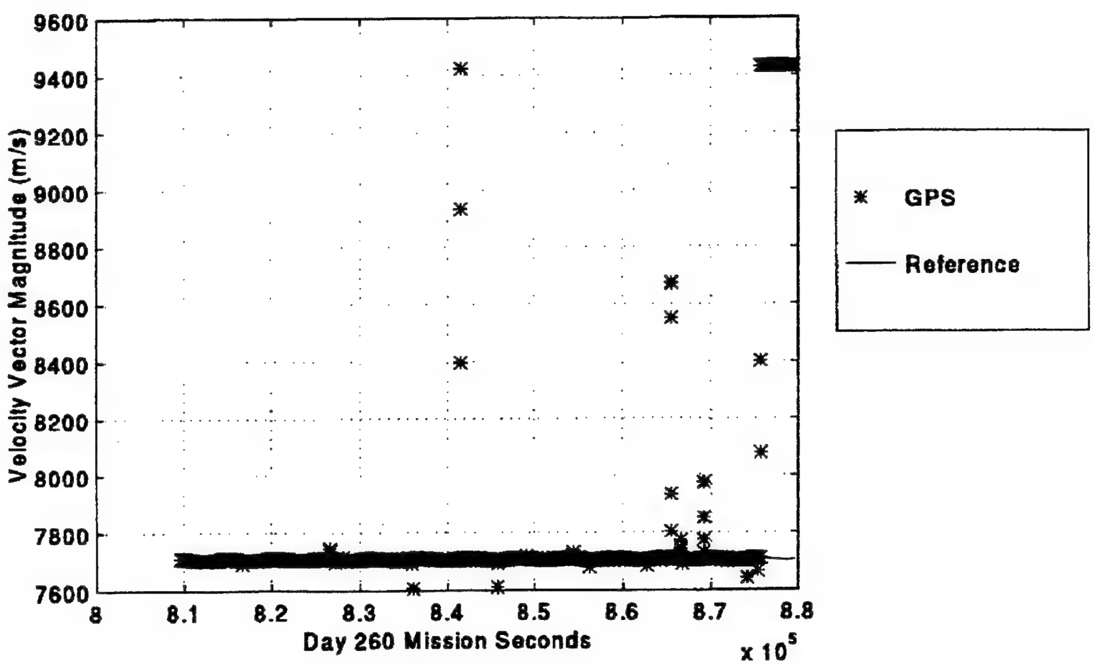


Figure 4.22. Day 260 Position and Velocity Vector Magnitude.

B. STK RESULTS

STK proved to be a valuable tool for visualizing the differences between the GPS vehicle tracks and the propagated vehicle tracks. The GPS vehicle is labeled "STS69gpsday#," and the propagated file vehicle is labeled "STS69propday#" where # corresponds to the last digit of the Julian date. The circle surrounding the vehicle represents the vehicle's field of view as seen by a horizon sensor mounted on the Shuttle. This field of view circle was helpful in discerning changes in altitude because it expanded as the vehicle's altitude increased.

The ground tracks displayed in Figure 4.23 show an example of the extreme differences that were occasionally encountered between the two data sets. This example occurs on day 250 and provides another look at the discrepancy observed in the Matlab plots for this day shown in Figure 4.18 and Figure 4.19. The two tracks eventually did coincide as shown in Figure 4.24. When the vehicle tracks coincided in this manner it was difficult to distinguish between them because they were plotted directly on top of each other.

Figure 4.25 is more typical of the STK plots obtained. This plot shows the entire ground track for day 251. The GPS and propagated ground tracks overlay directly on top of each other, and the differences between the two vehicles are indistinguishable because they are also plotted on top of each other. Figure 4.26 displays a variance in the data for day 251 showing the divergent tracks of the two vehicles. Each day's data analysis showed at least one anomaly similar to this one. The perspective shot in Figure 4.27 provides a better view of the difference between the two tracks. Figure 4.28 shows a similar error for day 253. The expanded field of view for the GPS vehicle indicates that there is a difference in altitude between the two vehicles.

A perspective view is shown in Figure 4.29 and displays how well the vehicles and orbits for day 255 match each other. Figure 4.30 is a close-up of the same picture and exhibits how closely the vehicles and two sets of orbits overlay on top of each other. Figure 4.31 further zooms in and reveals that the vehicles are separated, with the GPS track trailing the propagated track by a small distance.

Several possibilities exist as to why the GPS data and reference track data do not match directly. One possibility is that the error is caused by the transformation between reference frames that does not take into account pole wander or the irregular rotation rate of the Earth. Another possibility is a spurious data point from the GPS receiver. While these factors may contribute to the difference between the data sets, the largest source of error is most probably the fact that the files for the GPS track and the files for the reference track each had times that were rounded to the nearest whole second. With the Shuttle traveling at over 7 km/s this can result in considerable position differences between the two data sets particularly in the downtrack direction.

Figure 4.32 shows a GPS position data point at the center of a box whose sides were determined based on the velocity of the Shuttle in the X, Y and Z directions for a period of one second at a particular instant on day 251. This error box is approximately 6000 m long in the X direction, 2500 m wide in the Y direction and 1200 m high in the Z direction. As expected, the reference track data point for the same instant fell within the box. Figure 4.33 shows a plot of the differences between the GPS data and the NAVG-11 state vectors for day 251. The majority of the differences between the data sets lies within the box which encloses the error which may have been induced by a full second of timescale inaccuracy.

The most extreme example of divergence between the GPS and propagated tracks occurred on day 256 and is shown in Figure 4.34. In this plot the perspective view is from 150,000 km above the Earth and the small disc at the center is the Earth. Figure 4.35 is more indicative of the differences between vehicle tracks that were encountered. Typically an error in which the GPS track started to lead or lag the propagated vehicle would occur once per day.

The ground track plot for day 258 shown in Figure 4.36 reflects the sparse data for this flight day. The perspective view in Figure 4.37 shows how closely the two vehicle tracks match. The close-up view in Figure 4.38 also shows that the GPS track coincides with the propagated track. Figure 4.39 reveals that the two tracks are right on top of each other. The GPS orbit in this plot appears very smooth while the propagated orbit appears

to be segmented and not as smooth as the GPS orbit. This is expected since the GPS orbit is composed of considerably more data points.

The plot for day 259 shown in Figure 4.40 indicates some discrepancies between the GPS and propagated vehicle ground tracks. It shows two independent vehicles which indicates that the vehicle tracks diverge. Figure 4.41 further shows that the GPS data has produced a vehicle in a different orbit at a different inclination. This plot matches the Matlab three dimensional GPS orbit plot for this day shown in Figure 4.21.

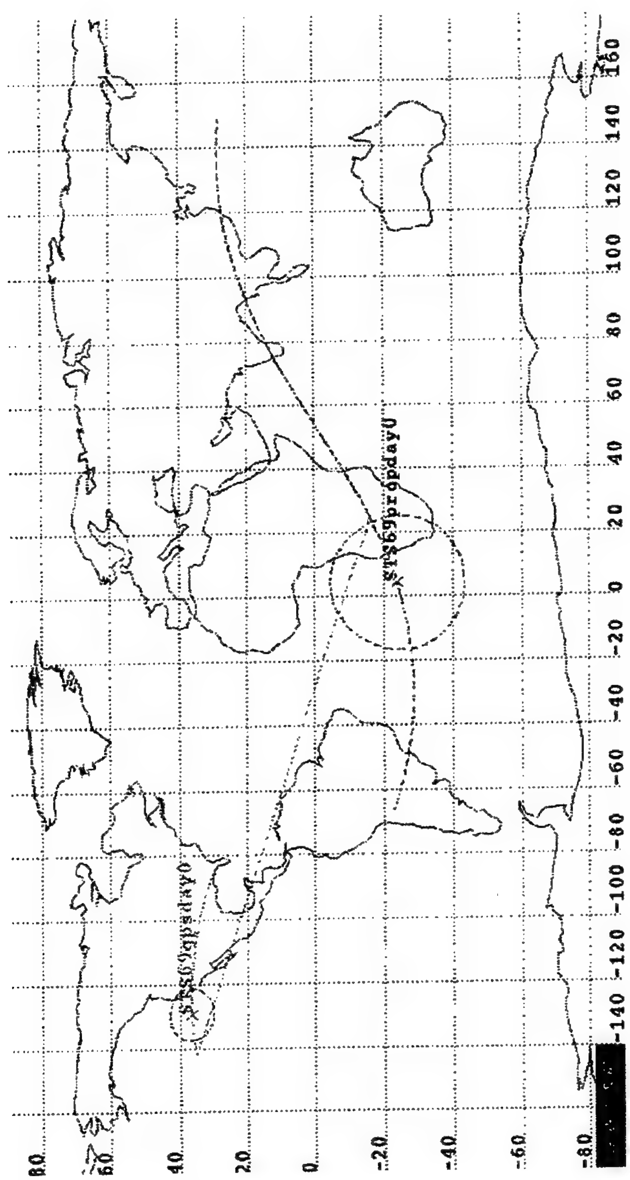


Figure 4.23. Day 250 STK Divergent Shuttle Vehicle Tracks.

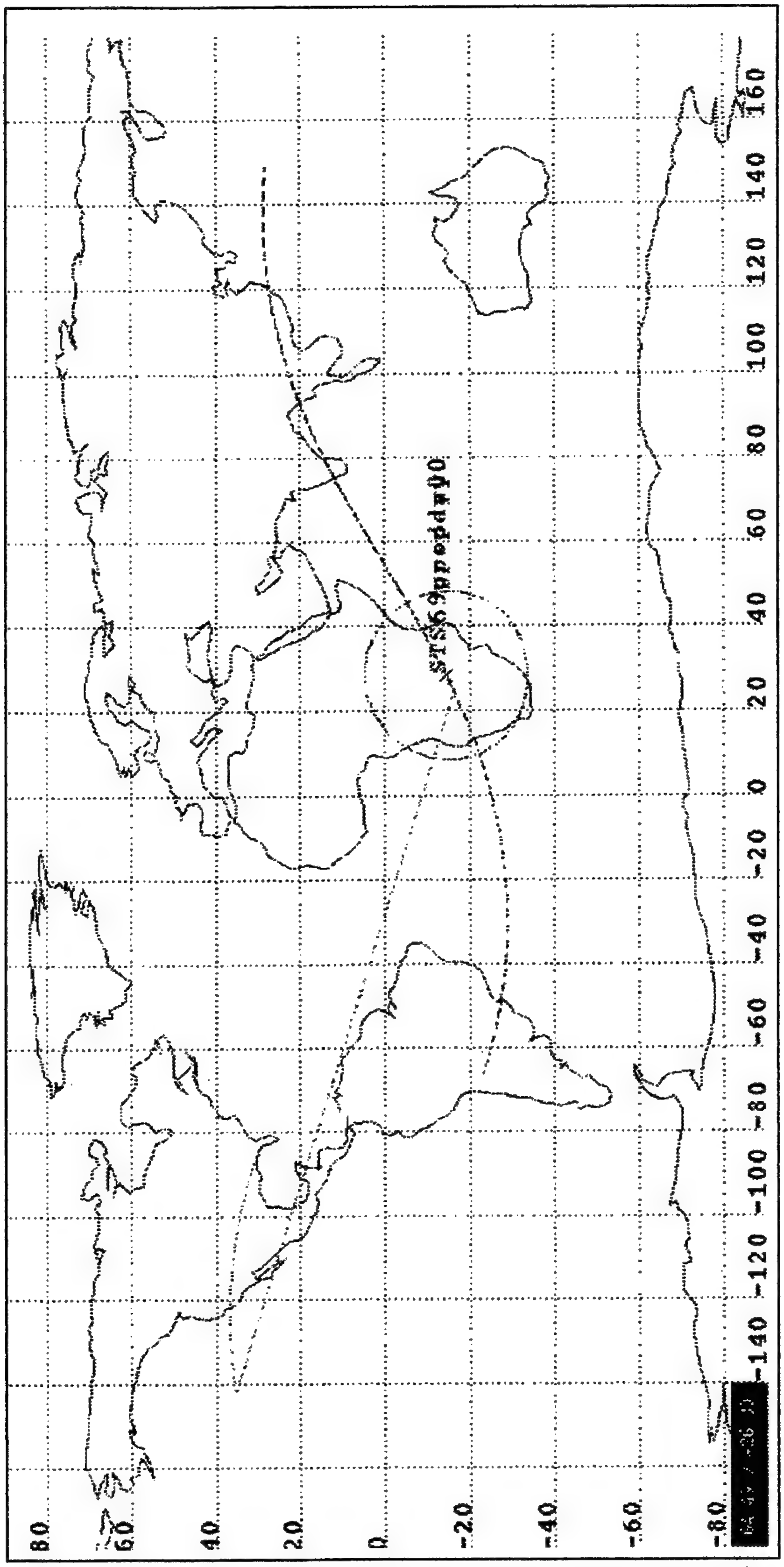


Figure 4.24. Day 250 STK Coincident Shuttle Vehicle Tracks.

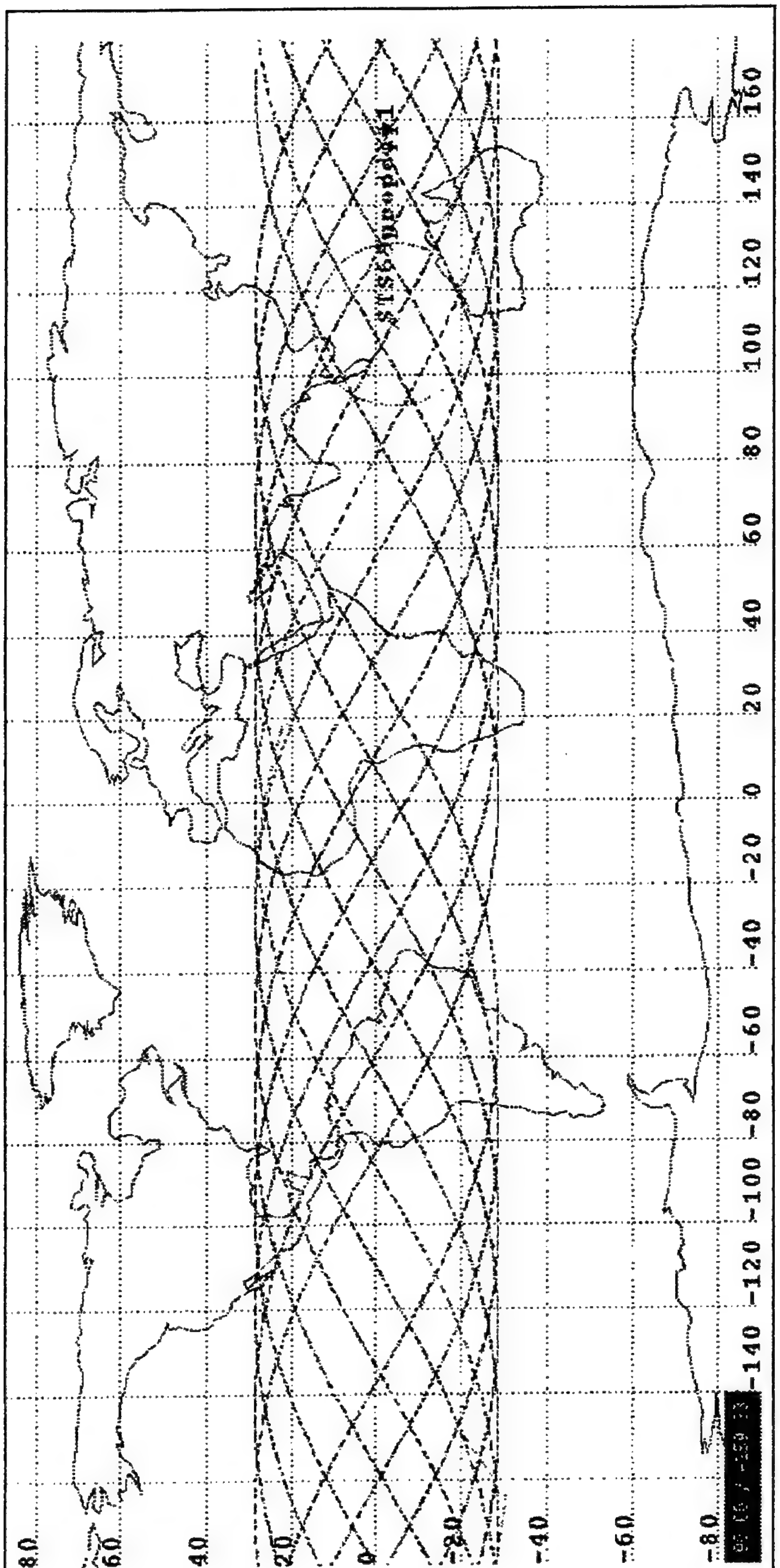


Figure 4.25. Day 251 STK Coincident Shuttle Vehicle Tracks.

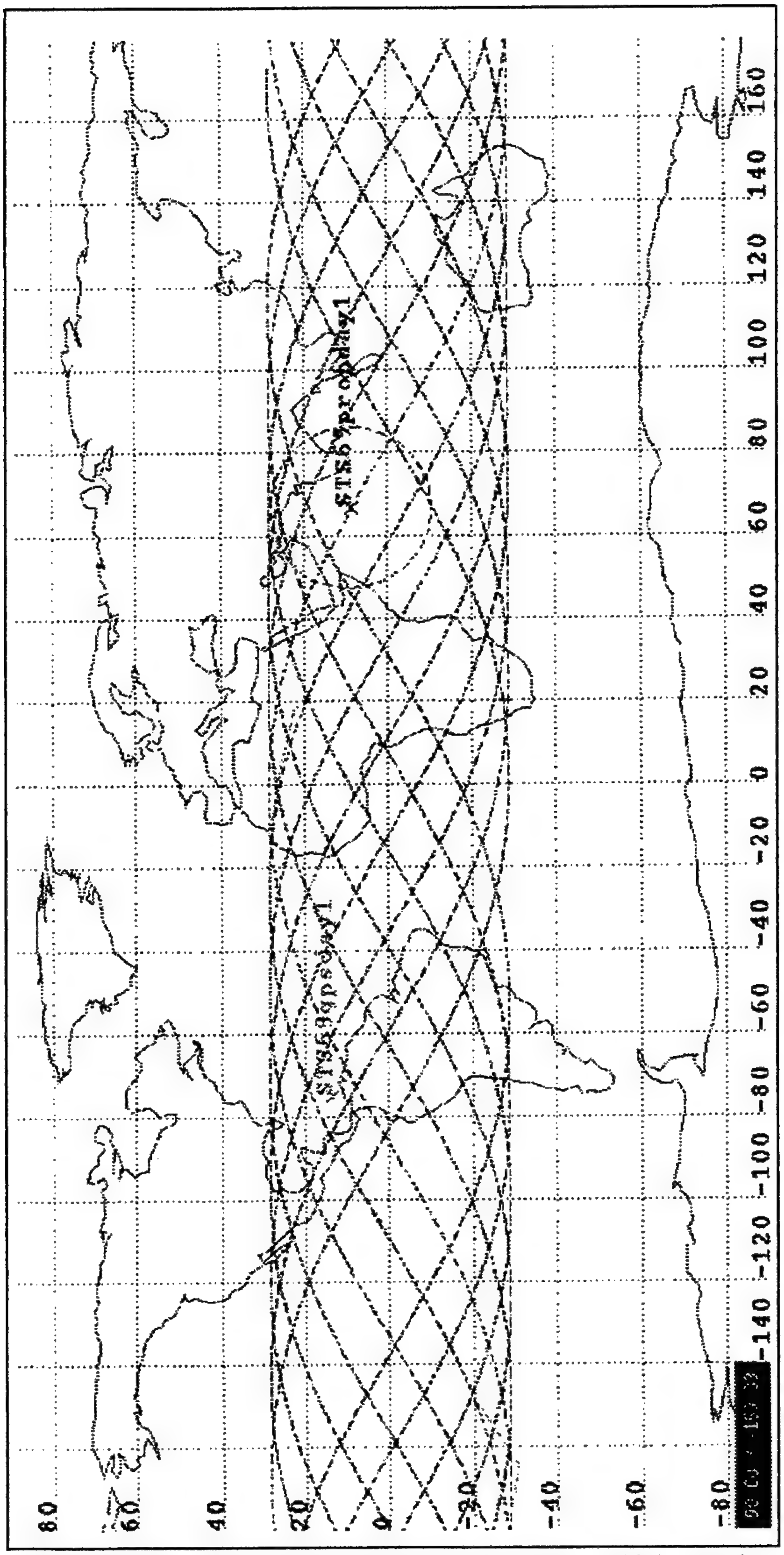


Figure 4.26. Day 251 STK Divergent Shuttle Vehicle Tracks.

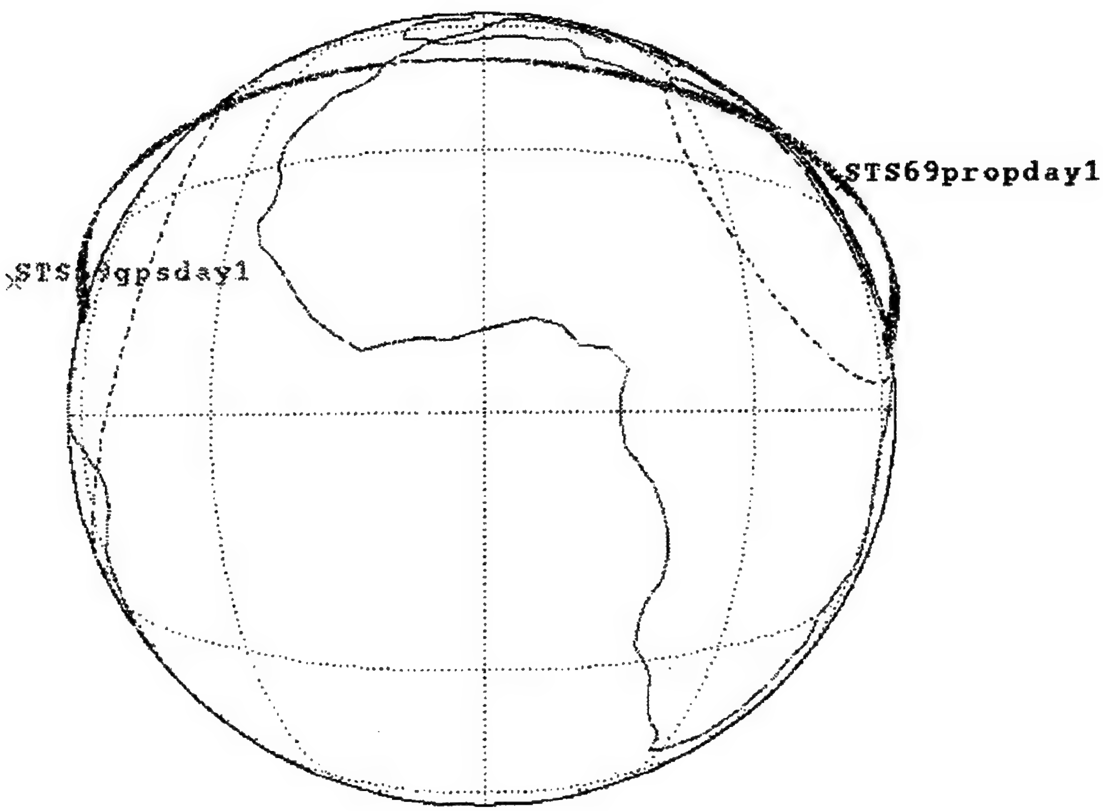


Figure 4.27. Day 251 STK Perspective View of Divergent Shuttle Vehicle Tracks.

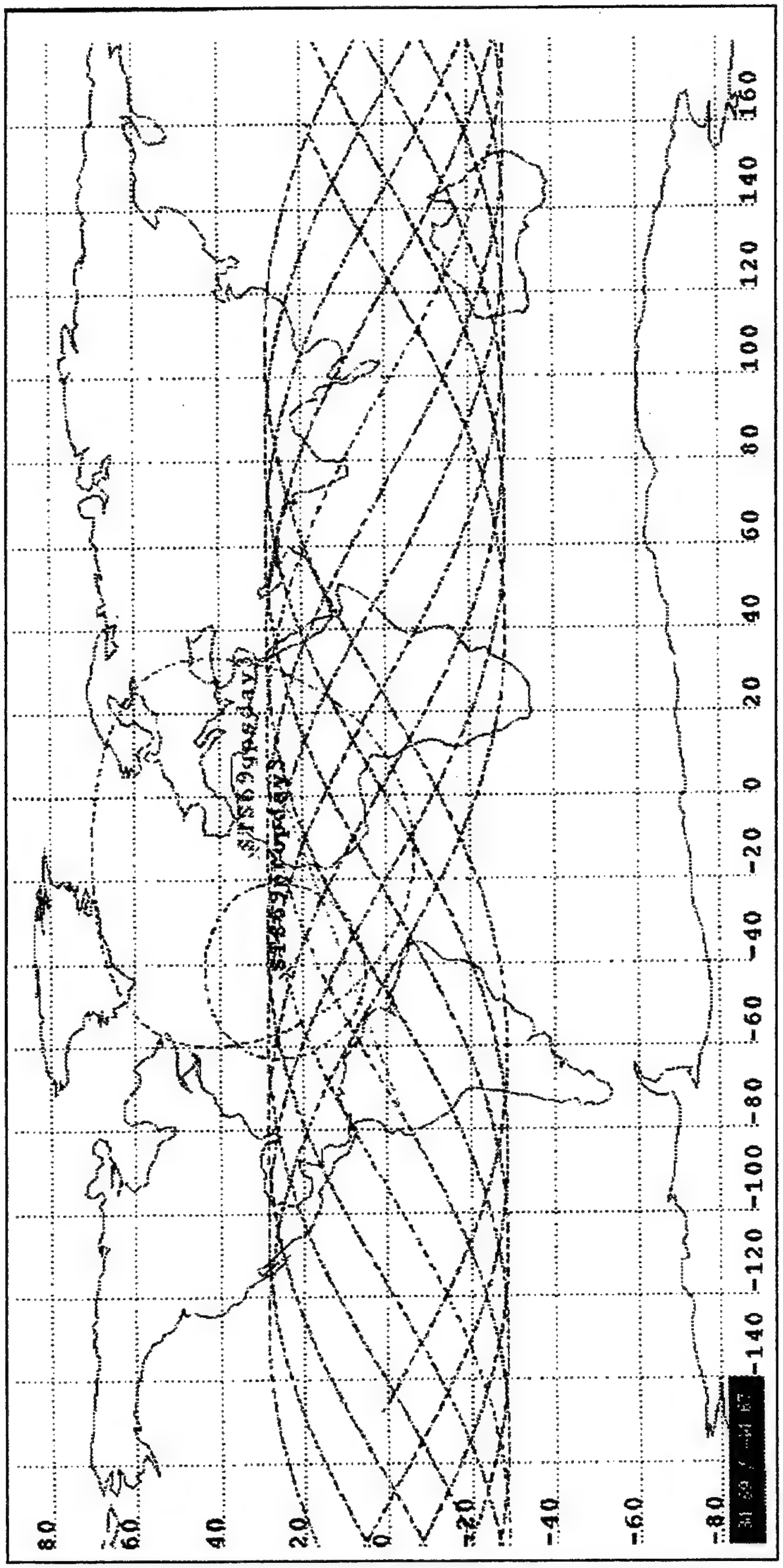


Figure 4.28. Day 253 STK Divergent Shuttle Vehicle Tracks.

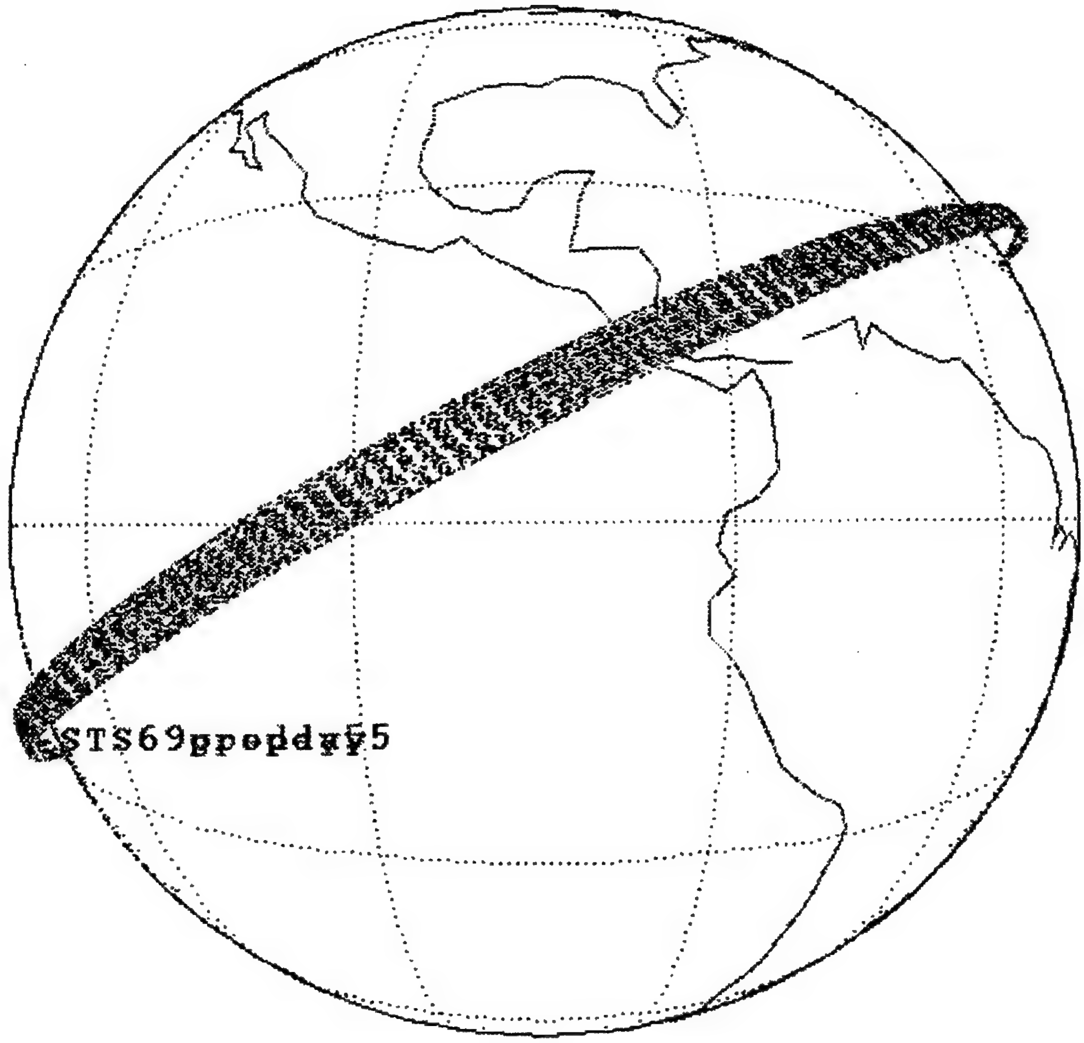


Figure 4.29. Day 255 STK Perspective View of Coincident Shuttle Vehicle Tracks.

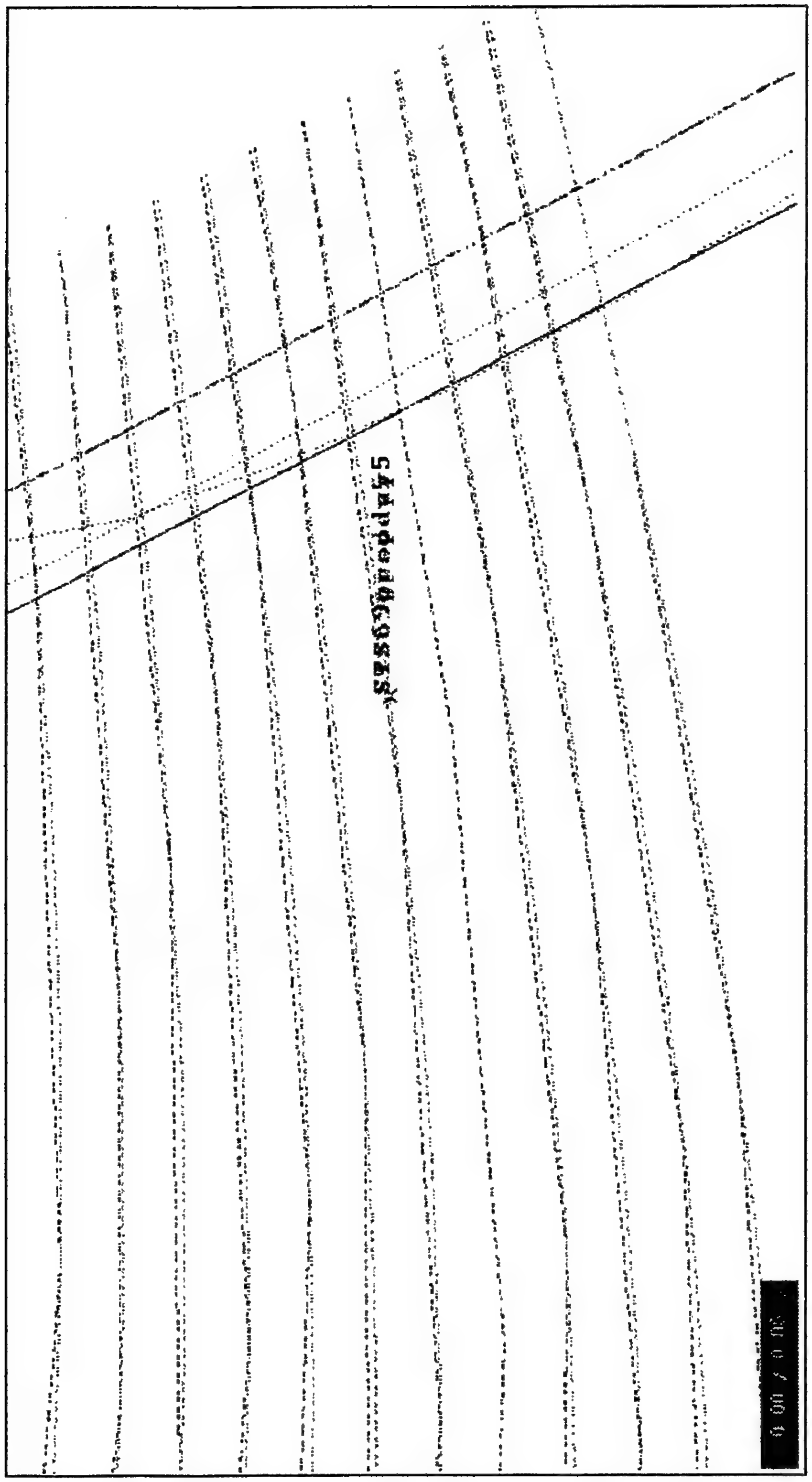


Figure 4.30. Day 255 Perspective View Close-up of Shuttle Vehicle Tracks.

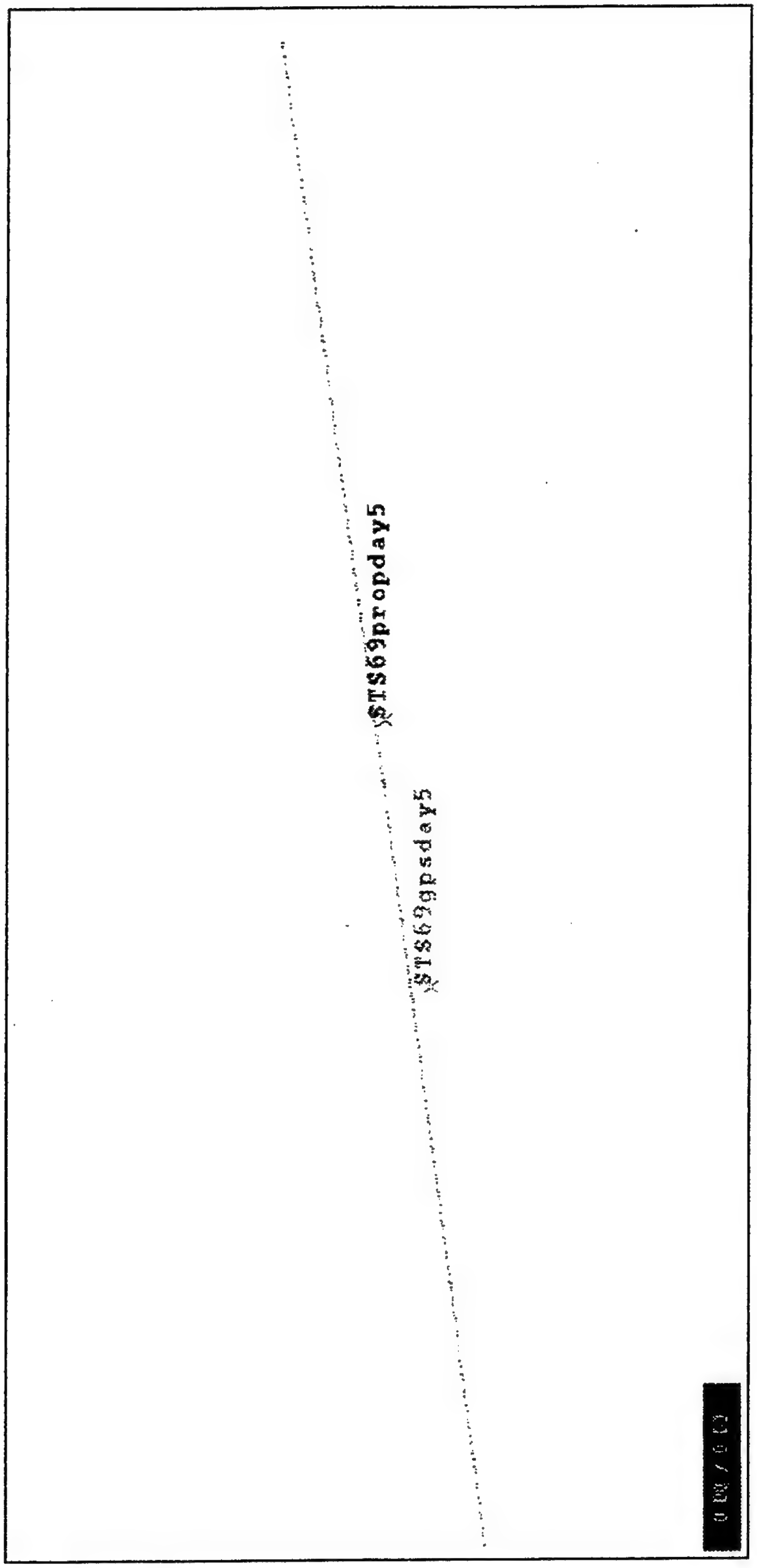


Figure 4.31. Day 255 STK Perspective View Close-up of Shuttle Vehicle Tracks.

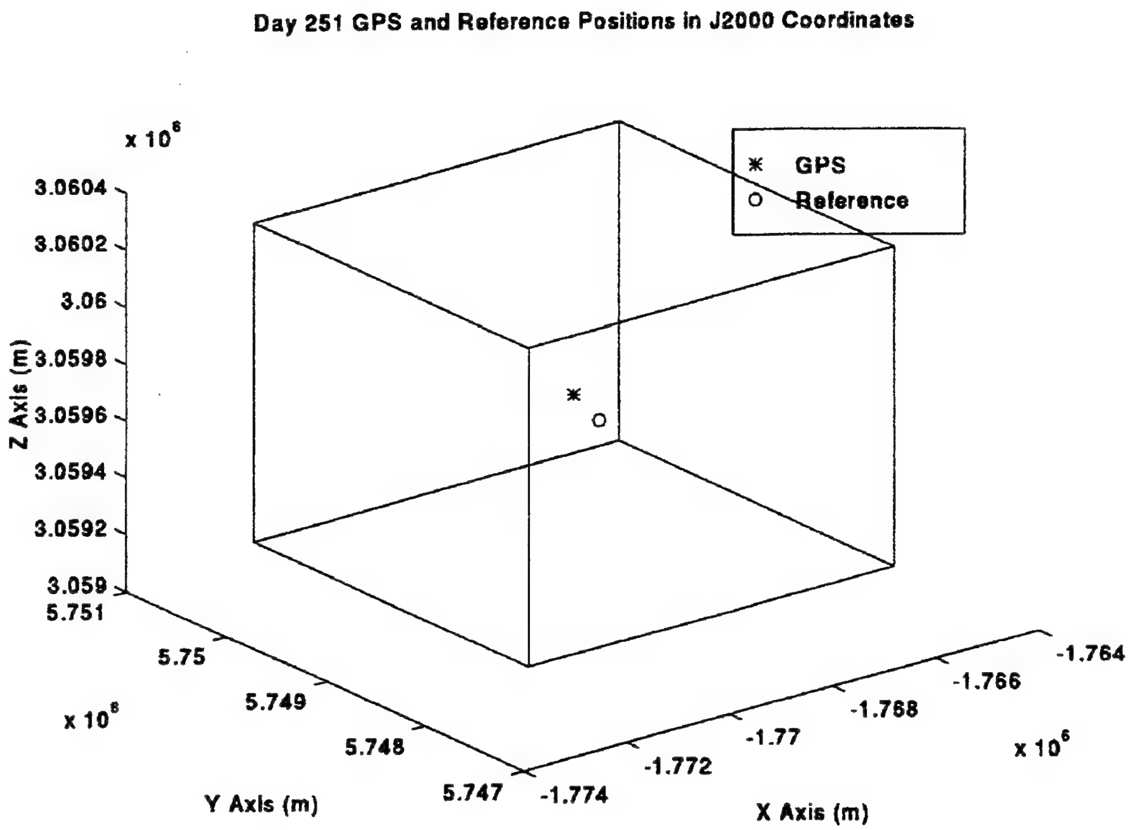


Figure 4.32. Day 251 GPS and Reference Positions in J2000 Coordinates.

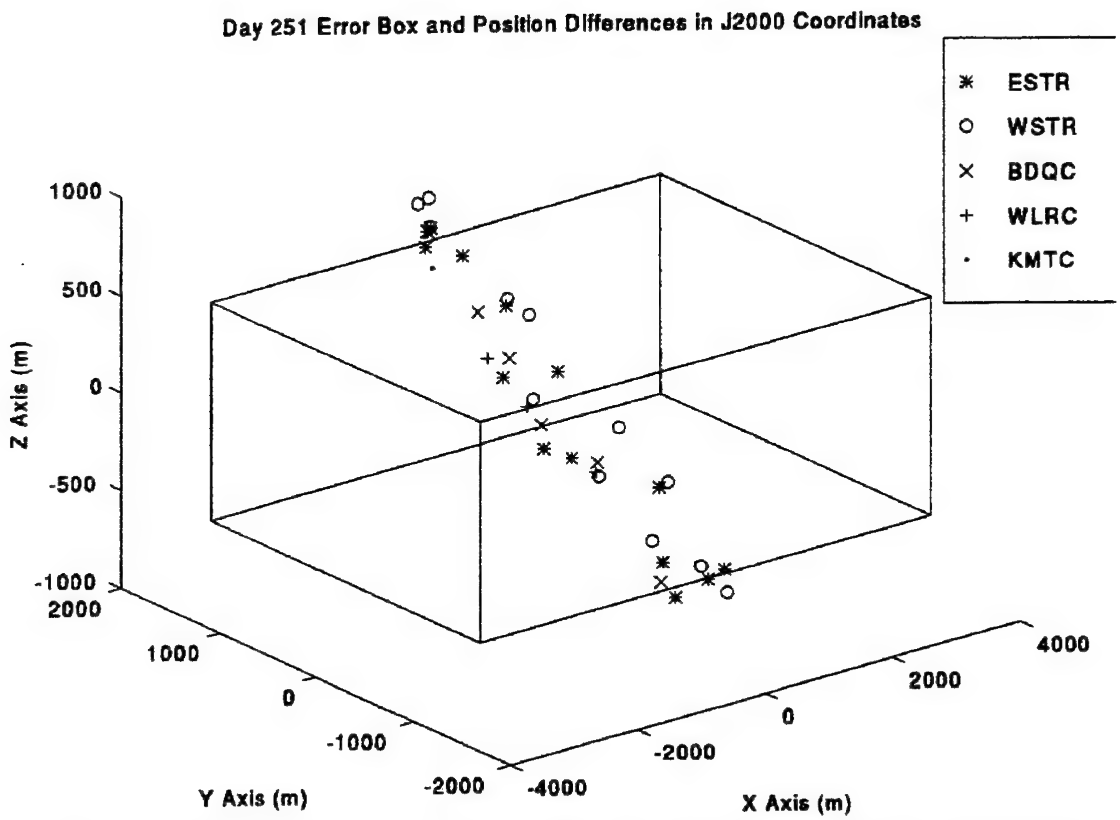


Figure 4.33. Day 251 Error Box and Position Differences in J2000 Coordinates.

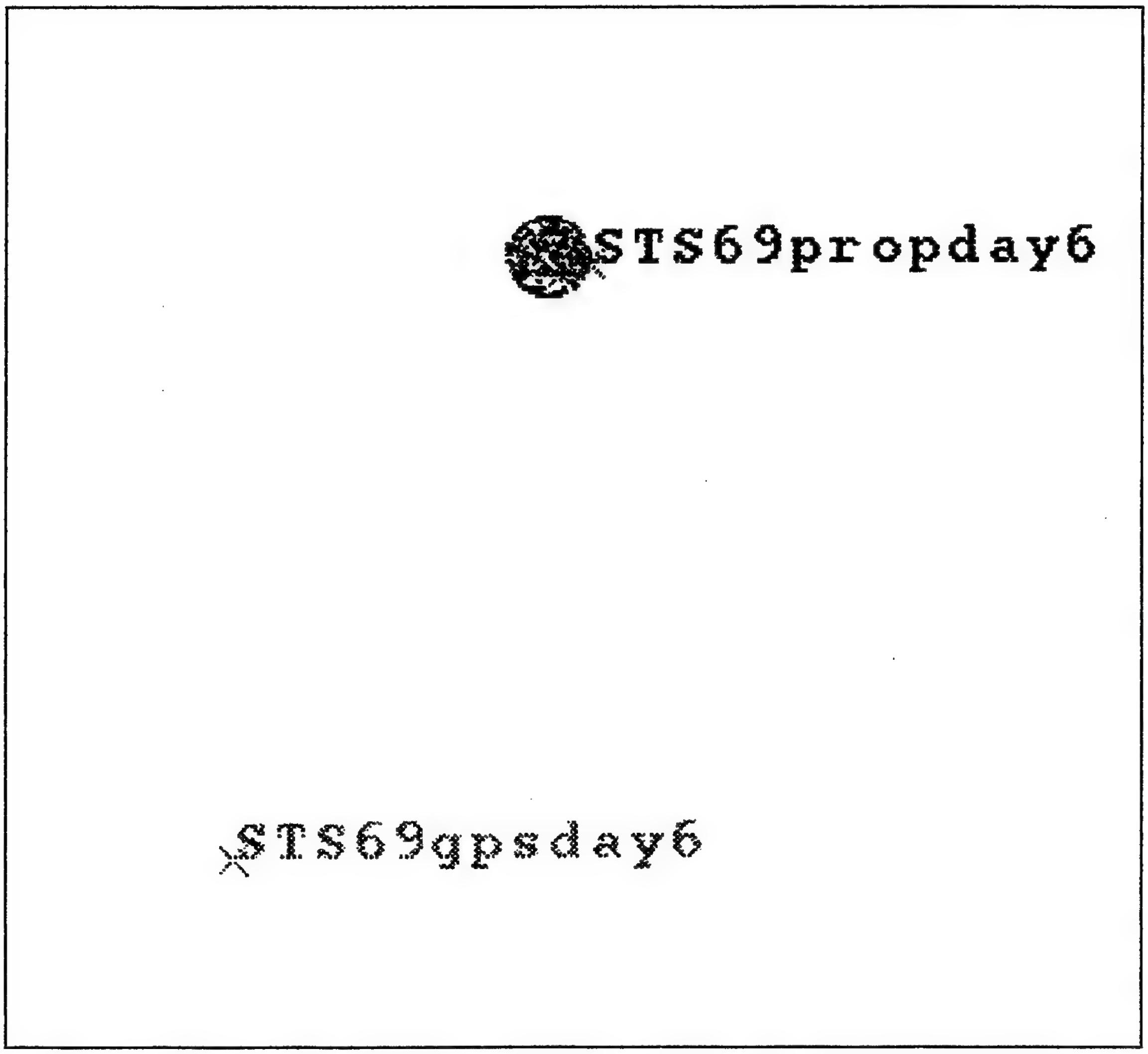


Figure 4.34. Day 256 STK Perspective View of Divergent Shuttle Vehicle Tracks.

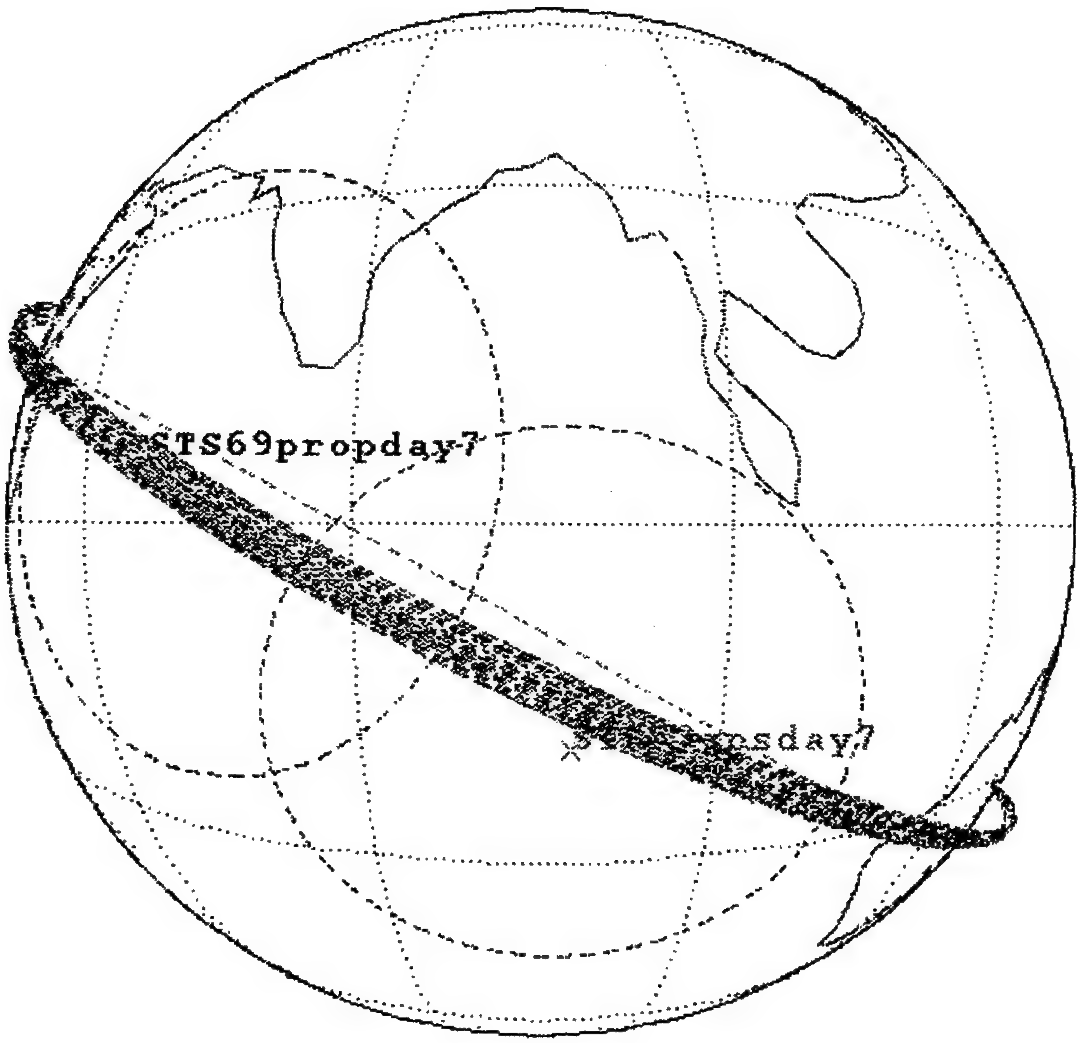


Figure 4.35. Day 257 STK Perspective View of Divergent Shuttle Vehicle Tracks.

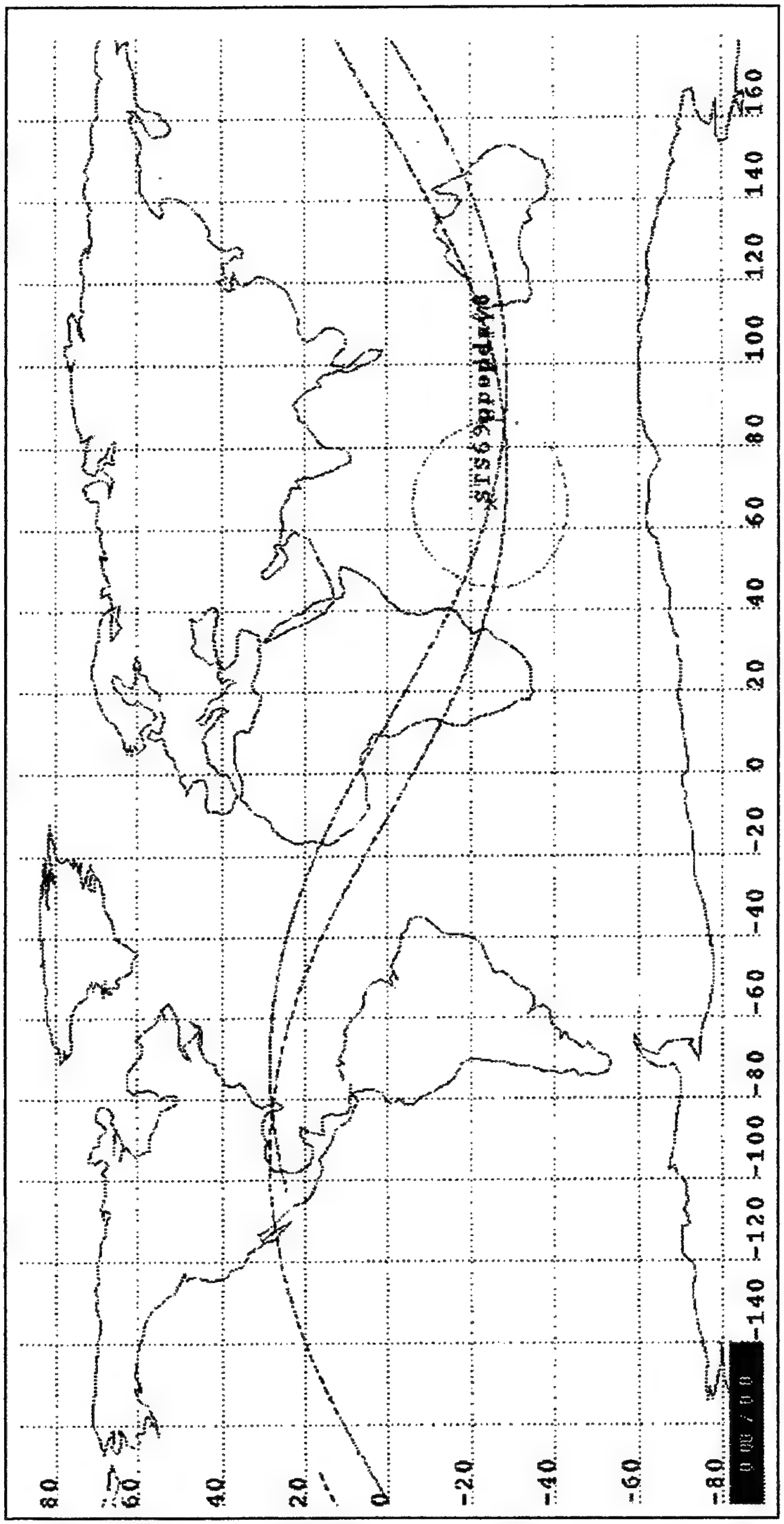


Figure 4.36. Day 258 STK Coincident Shuttle Vehicle Tracks.

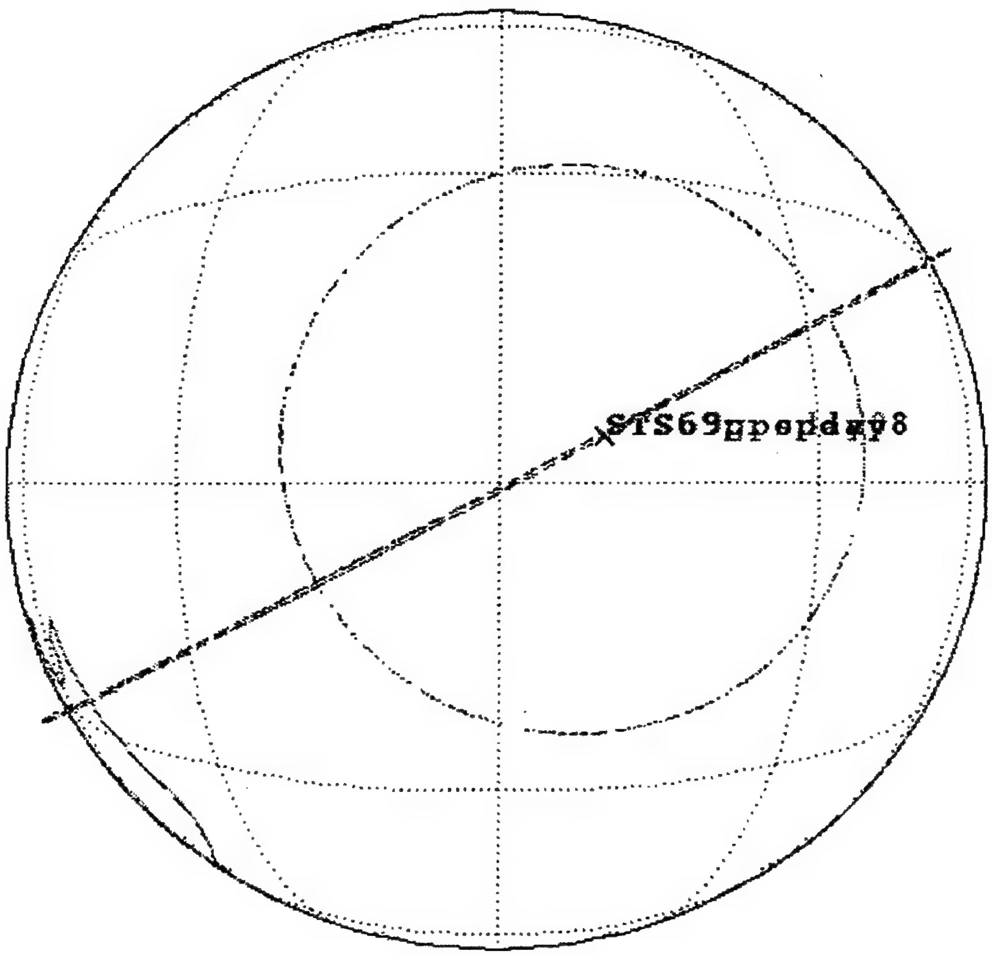


Figure 4.37. Day 258 STK Perspective View of Coincident Shuttle Vehicle Tracks.

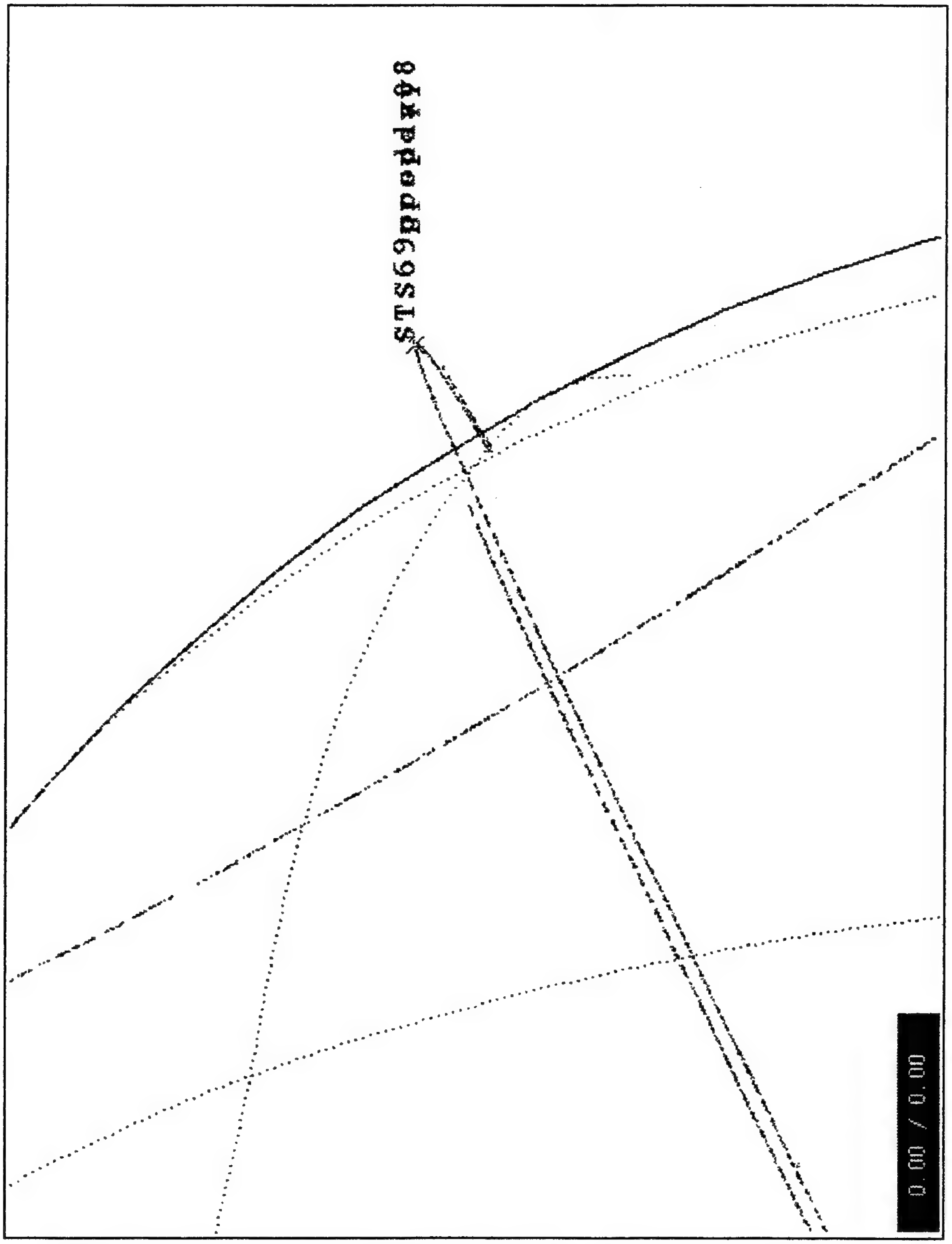


Figure 4.38. Day 258 STK Perspective View Close-up of Shuttle Vehicle Tracks.

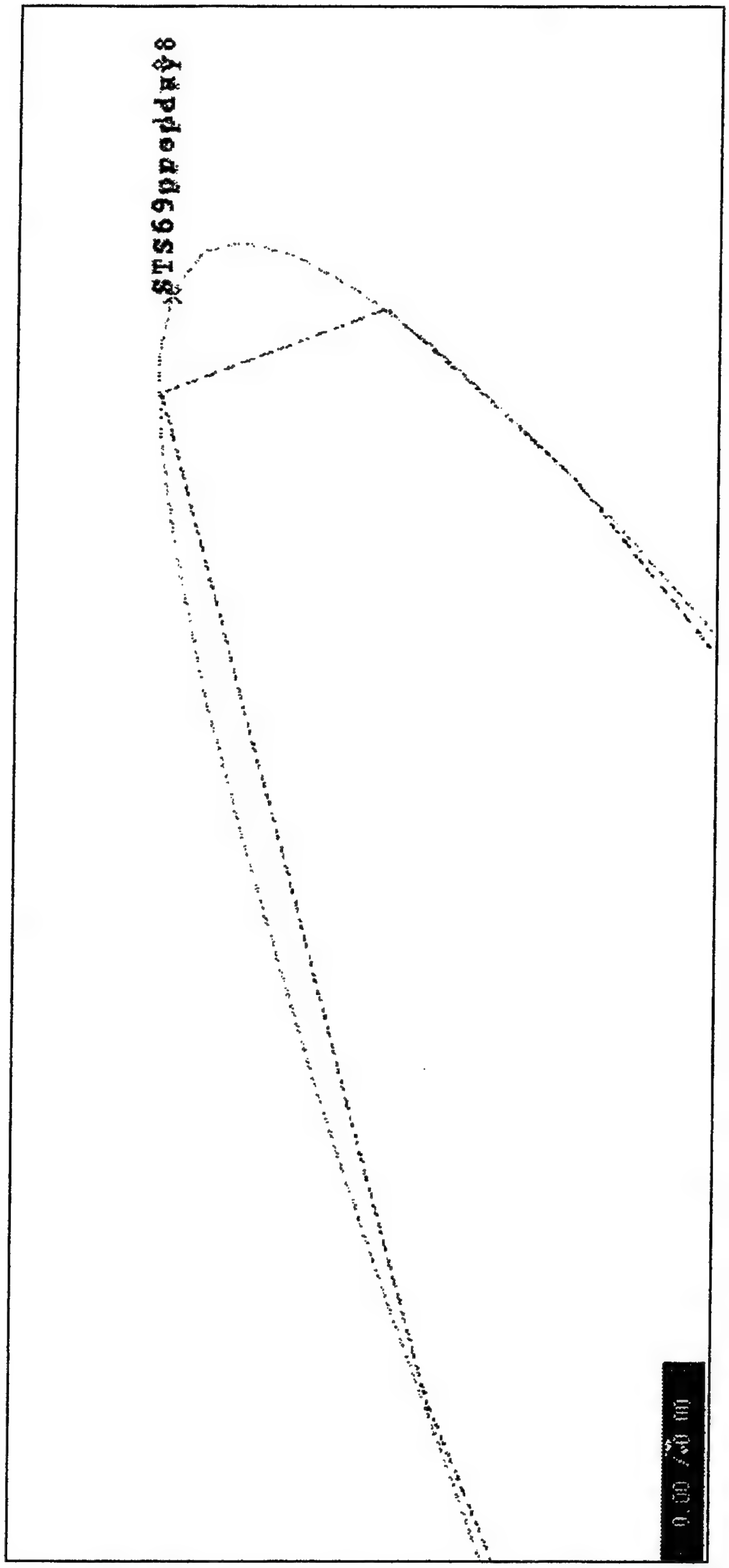


Figure 4.39. Day 258 STK Perspective View Close-up of Shuttle Vehicle Tracks.

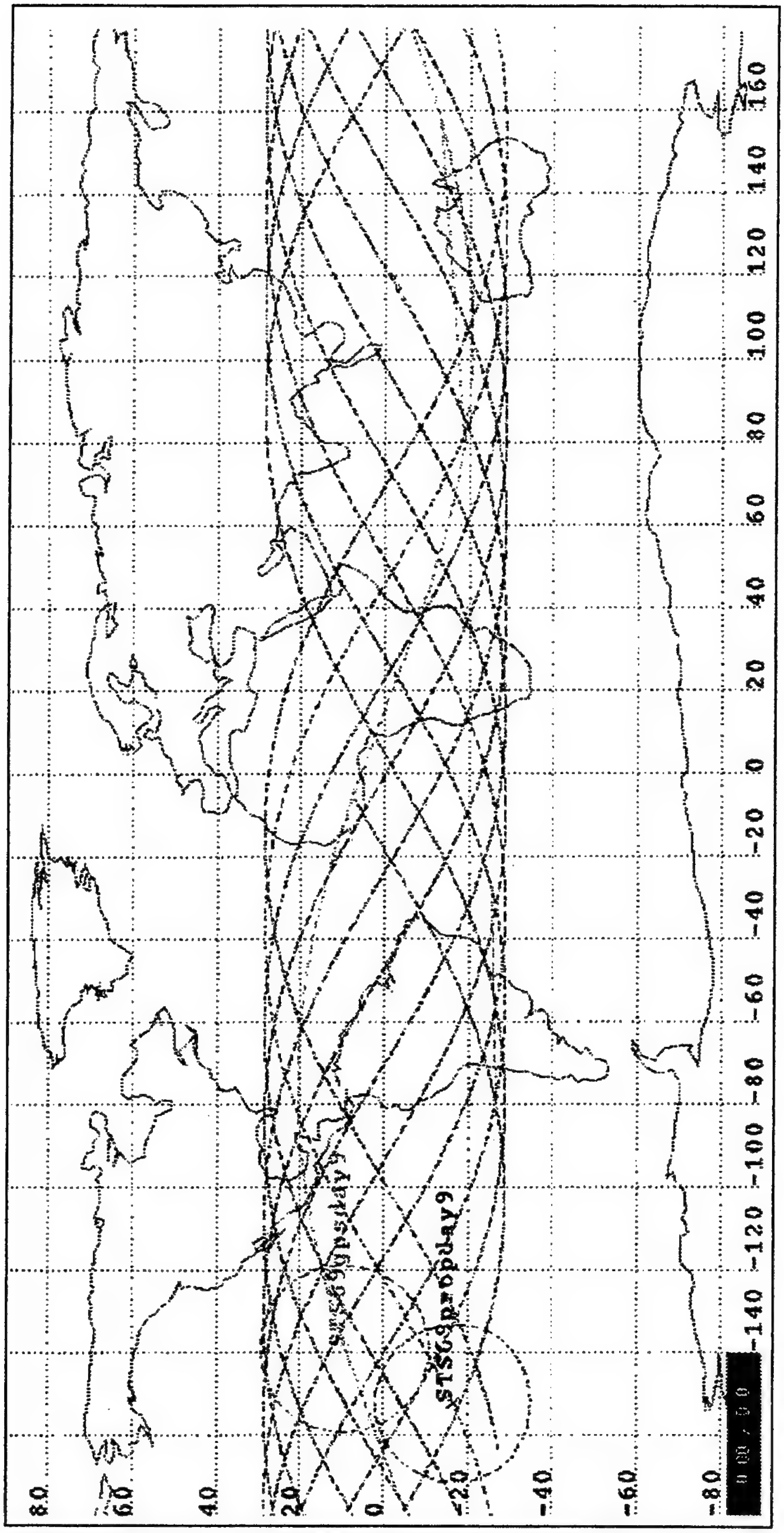


Figure 4.40. Day 259 STK Divergent Shuttle Vehicle Tracks.

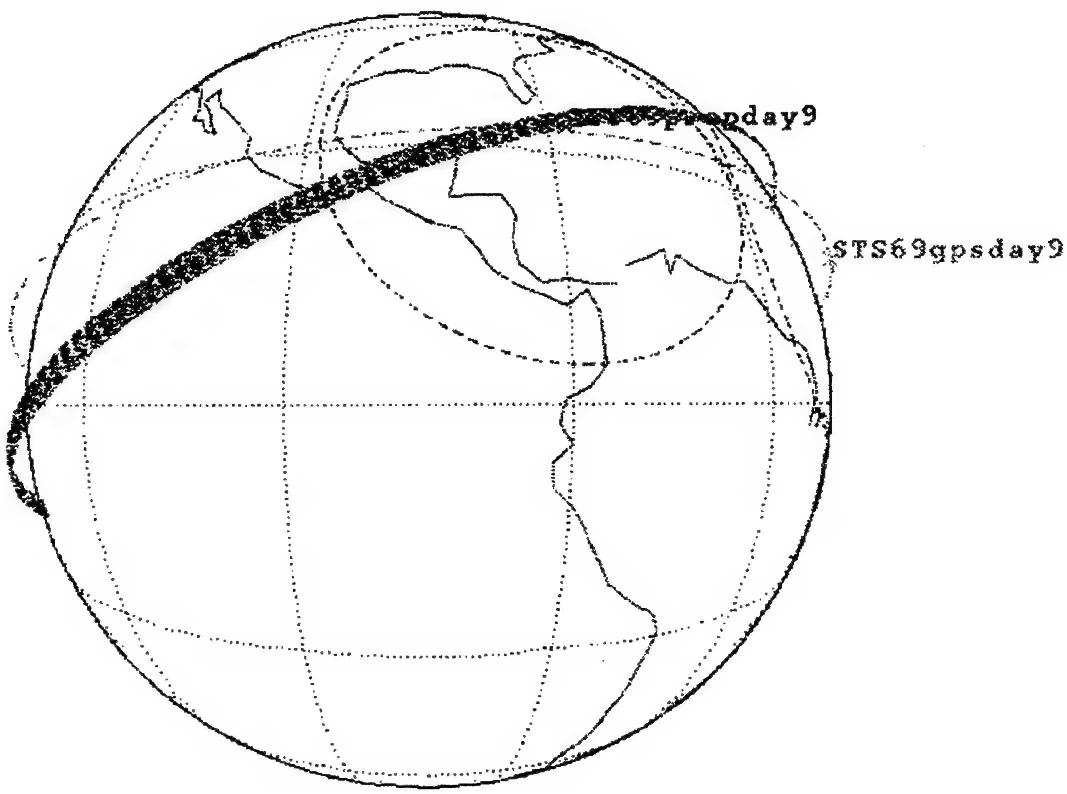


Figure 4.41. Day 259 STK Perspective View of Divergent Shuttle Vehicle Tracks.

C. SHUTTLE UEN COMPARISON RESULTS

1. UEN transformation

In an effort to better classify the state vector errors encountered as errors in the crosstrack direction, in the downtrack direction, or in altitude, the GPS and NAVG-11 state vectors with matching times were transformed from J2000 coordinates to the Shuttle's UEN frame. In order to perform the transformation from the J2000 reference frame to the Shuttle UEN reference frame as shown in Figure 4.42, two Euler angle rotations must be performed. A rotation about the Z-axis by a value of γ followed by a rotation about the Y-axis by $-\delta$ are required as shown in Equations 4.1, 4.2 and 4.3.

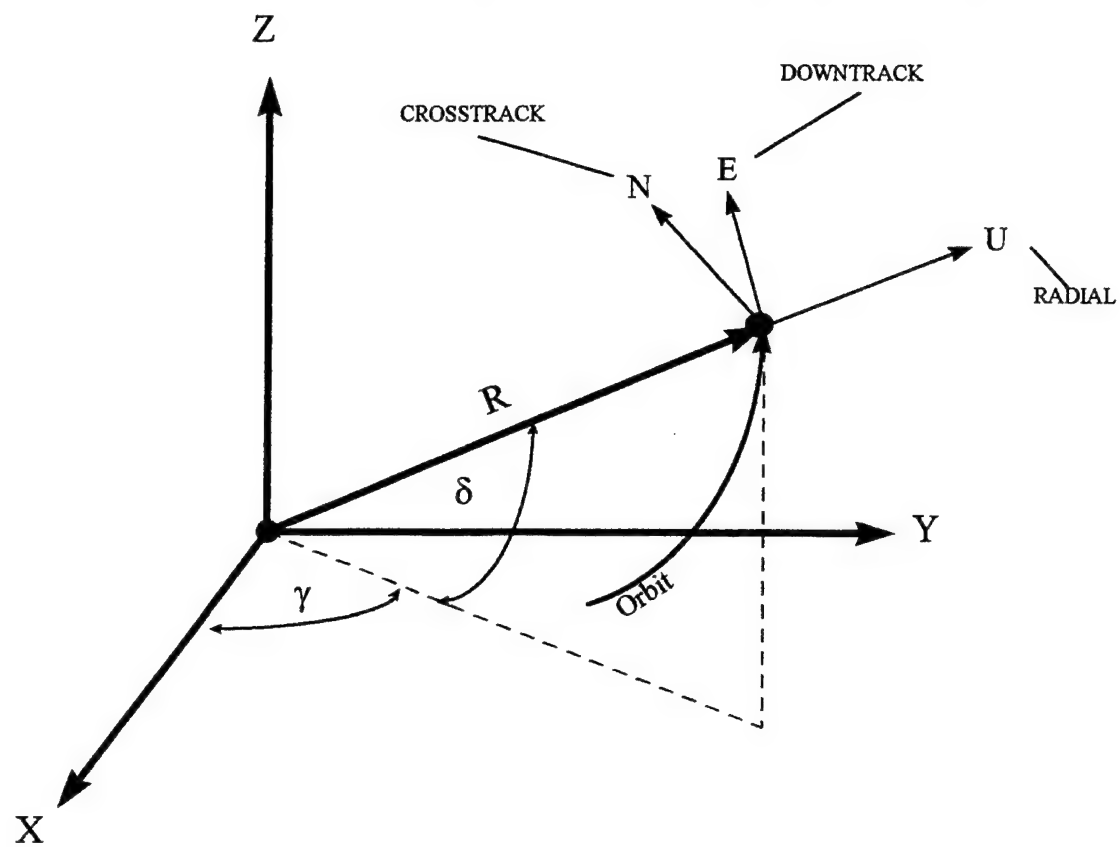


Figure 4.42. Up-East-North Reference Frame.

$$\begin{bmatrix} U \\ E \\ N \end{bmatrix}_{Shuttle} = C_y(-\delta)\, C_z(\gamma) \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{J2000} \tag{4.1}$$

$$\begin{bmatrix} U \\ E \\ N \end{bmatrix}_{Shuttle} = \begin{bmatrix} \cos(-\delta) & 0 & -\sin(-\delta) \\ 0 & 1 & 0 \\ \sin(-\delta) & 0 & \cos(-\delta) \end{bmatrix} \begin{bmatrix} \cos(\gamma) & \sin(\gamma) & 0 \\ -\sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{J2000} \tag{4.2}$$

$$\begin{bmatrix} U \\ E \\ N \end{bmatrix}_{Shuttle} = \begin{bmatrix} \cos(\delta)\cos(\gamma) & \cos(\delta)\sin(\gamma) & \sin(\delta) \\ \sin(\delta) & \cos(\gamma) & 0 \\ -\sin(\delta)\cos(\gamma) & -\sin(\delta)\sin(\gamma) & \cos(\delta) \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{J2000} \tag{4.3}$$

2. UEN results

This transformation was implemented using Matlab and is available in Appendix G. The following results shown in Tables 4.2 and 4.3 and Figures 4.43, 4.44, 4.45, 4.49, 4.50 and 4.51 at the end of the chapter were obtained from the day 251 and day 252 state vector position differences.

	Vertical (m)	Downtrack (m)	Crosstrack (m)
Average	12.1	5.5	0
Median	13.2	85.7	0
Standard Deviation	53.8	1461.0	0

Table 4.2. Day 251 State Vector Position differences.

	Vertical (m)	Downtrack (m)	Crosstrack (m)
Average	2.4	-32.7	0
Median	8.0	-140.0	0
Standard Deviation	53.8	1348.9	0

Table 4.3. Day 252 State Vector Position differences.

The vertical position differences shown in Figure 4.43 and 4.49 were less than the expected one sigma value of 75 m for SPS. The values obtained for vertical position difference matched the values obtained from the position vector magnitude (altitude) difference plot when the data sets were analyzed in the J2000 reference frame. These values are within the expected SPS 156 m vertical positioning accuracy.

Although the average downtrack position difference was fairly small for both days, the extremely large standard deviation indicates that significant downtrack errors were encountered. When traveling at 7 km/s a downtrack error of 1400 m corresponds to a 0.2 s error in time. It was expected that a constant position error in the downtrack direction would be observed. The downtrack position differences displayed in Figure 4.44 and Figure 4.50 varied approximately ±1400 m, and no constant offset was discovered. These results far exceeded the SPS one sigma horizontal positioning error of 50 m.

Crosstrack errors were all less than 1×10^{-8} m for both days as shown in Figure 4.45 and Figure 4.51. This was beyond the precision of the data, and makes the differences essentially zero. These results were unexpected and did not match the one sigma horizontal position error of 50 m for SPS. Due to unidentified sources of error, no firm conclusions can be drawn; however, the downtrack and crosstrack errors seem to indicate that most of the position error is in the downtrack direction.

	Vertical (m/s)	Downtrack (m/s)	Crosstrack (m/s)
Average	0.29	0.83	-0.16
Median	0.70	0.11	-0.13
Standard Deviation	4.18	2.15	0.96

Table 4.4. Day 251 State Vector Velocity differences.

	Vertical (m/s)	Downtrack (m/s)	Crosstrack (m/s)
Average	0.58	1.13	-0.06
Median	0.38	0.39	-0.15
Standard Deviation	4.08	2.34	1.53

Table 4.5. Day 252 State Vector Velocity differences.

The velocity results from the comparison of state vectors for day 251 and day 252 are shown in Tables 4.4 and 4.5 and Figures 4.46, 4.47, 4.48, 4.52, 4.53 and 4.54. Both days' results are very similar. In general the average values for vertical and downtrack velocity differences exceeded the expected SPS one sigma velocity accuracy of 0.5 m/s, and the median values were close to this value. The crosstrack velocity data is well within the expected SPS one sigma velocity accuracy.

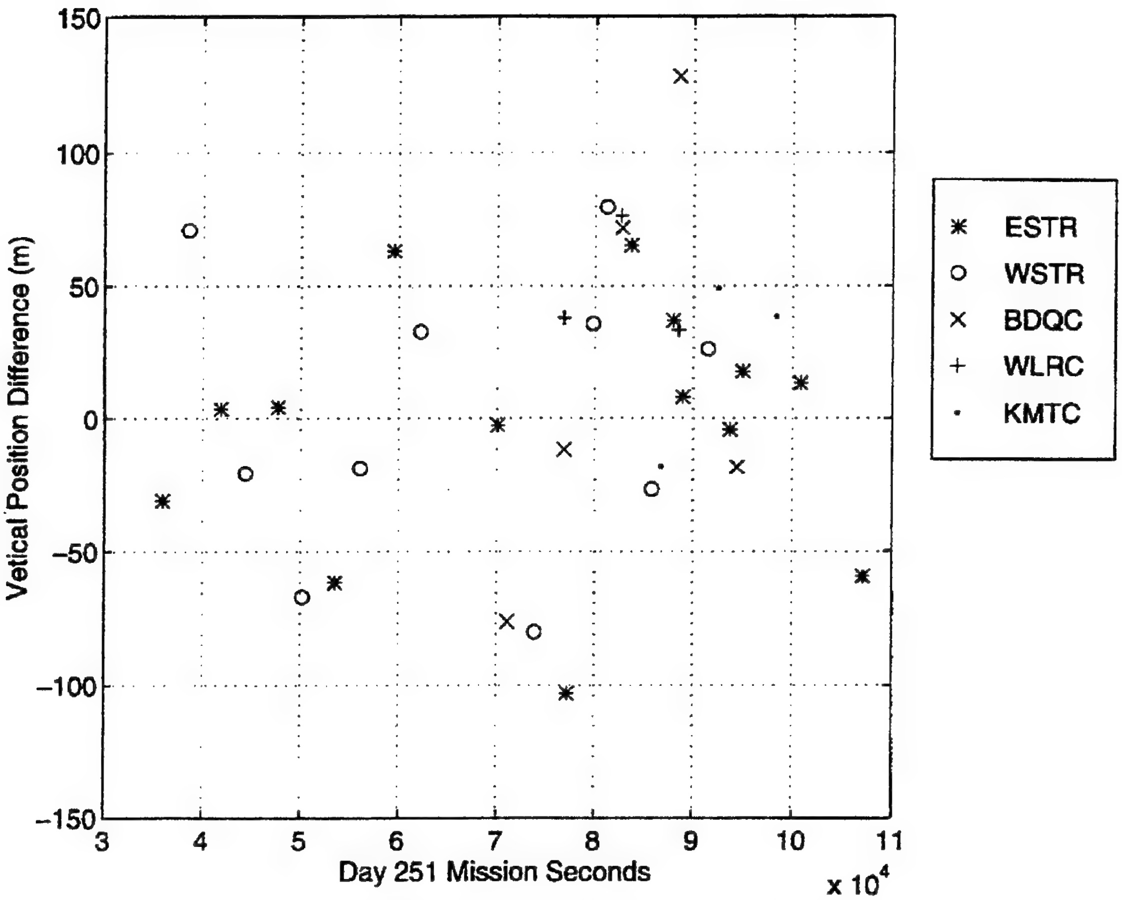


Figure 4.43. Day 251 Vertical Position Difference.

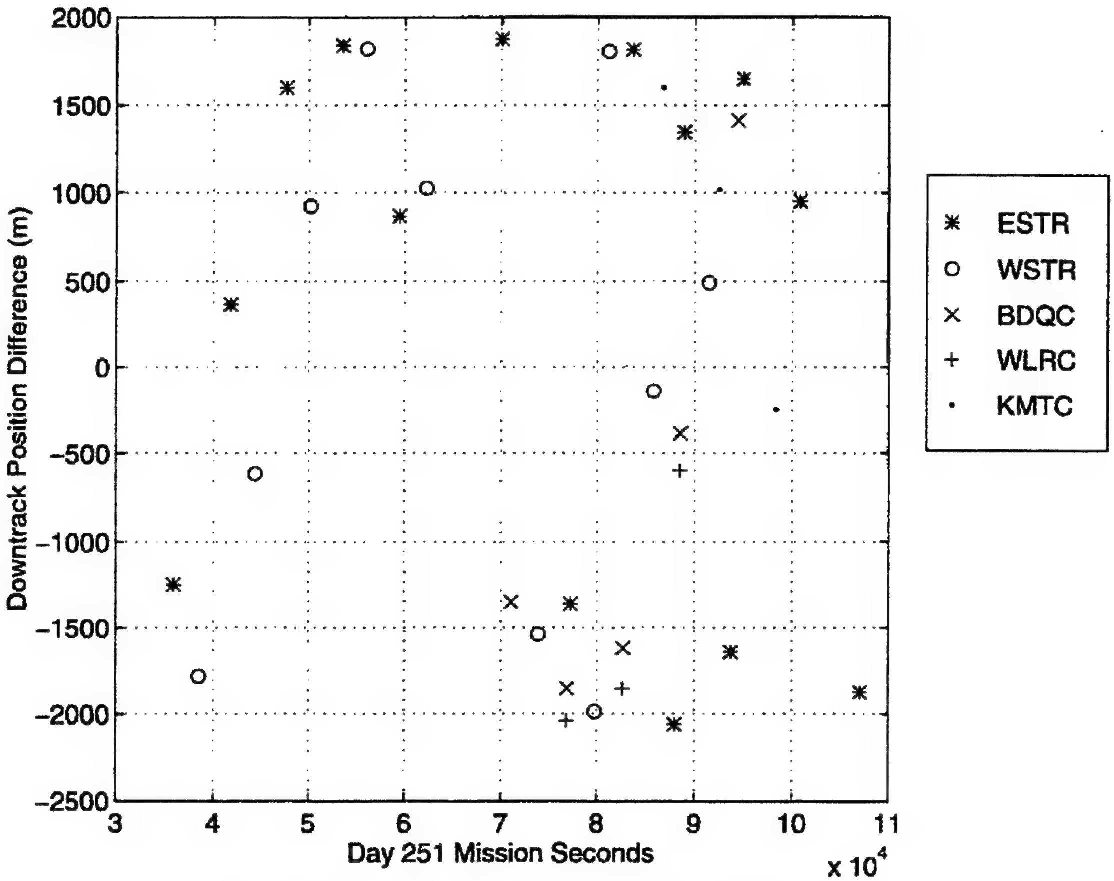


Figure 4.44. Day 251 Downtrack Position Difference.

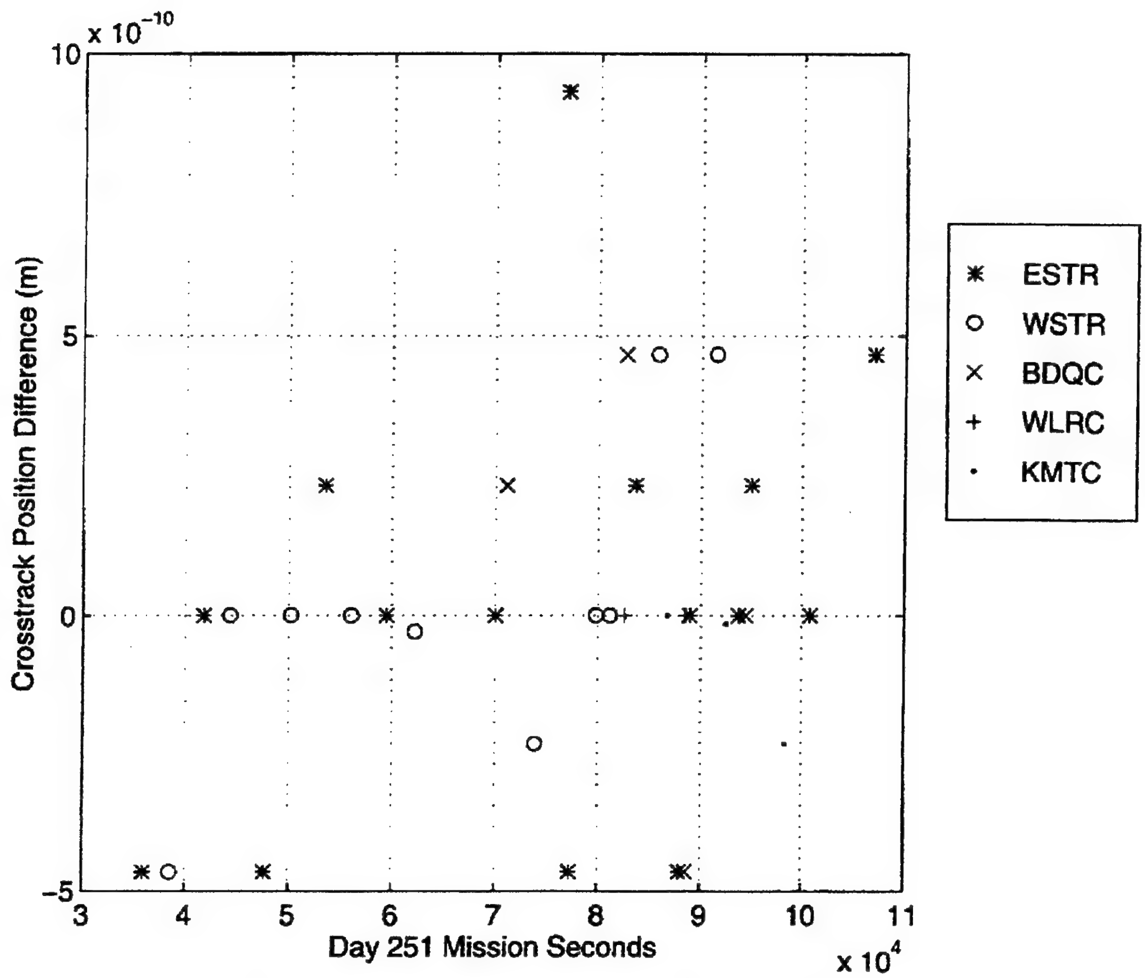


Figure 4.45. Day 251 Crosstrack Position Difference.

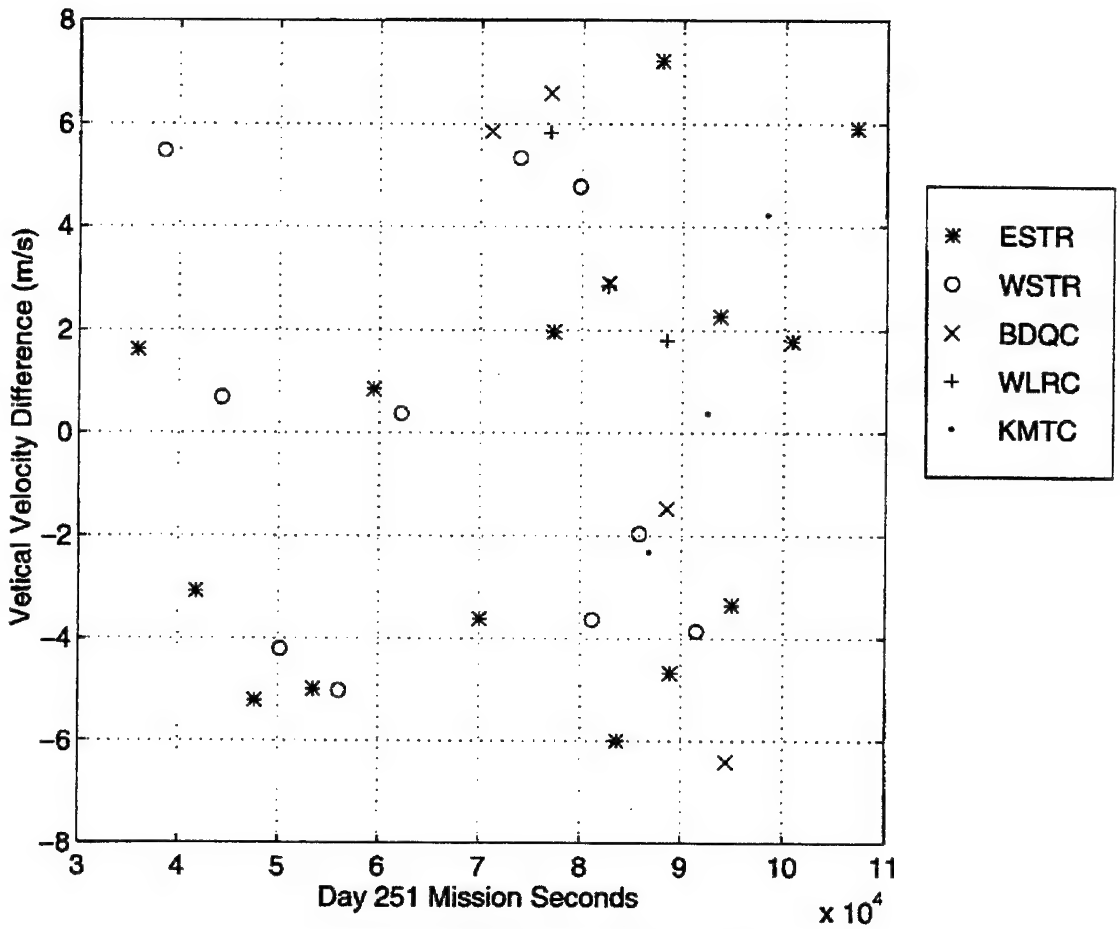


Figure 4.46. Day 251 Vertical Velocity Difference.

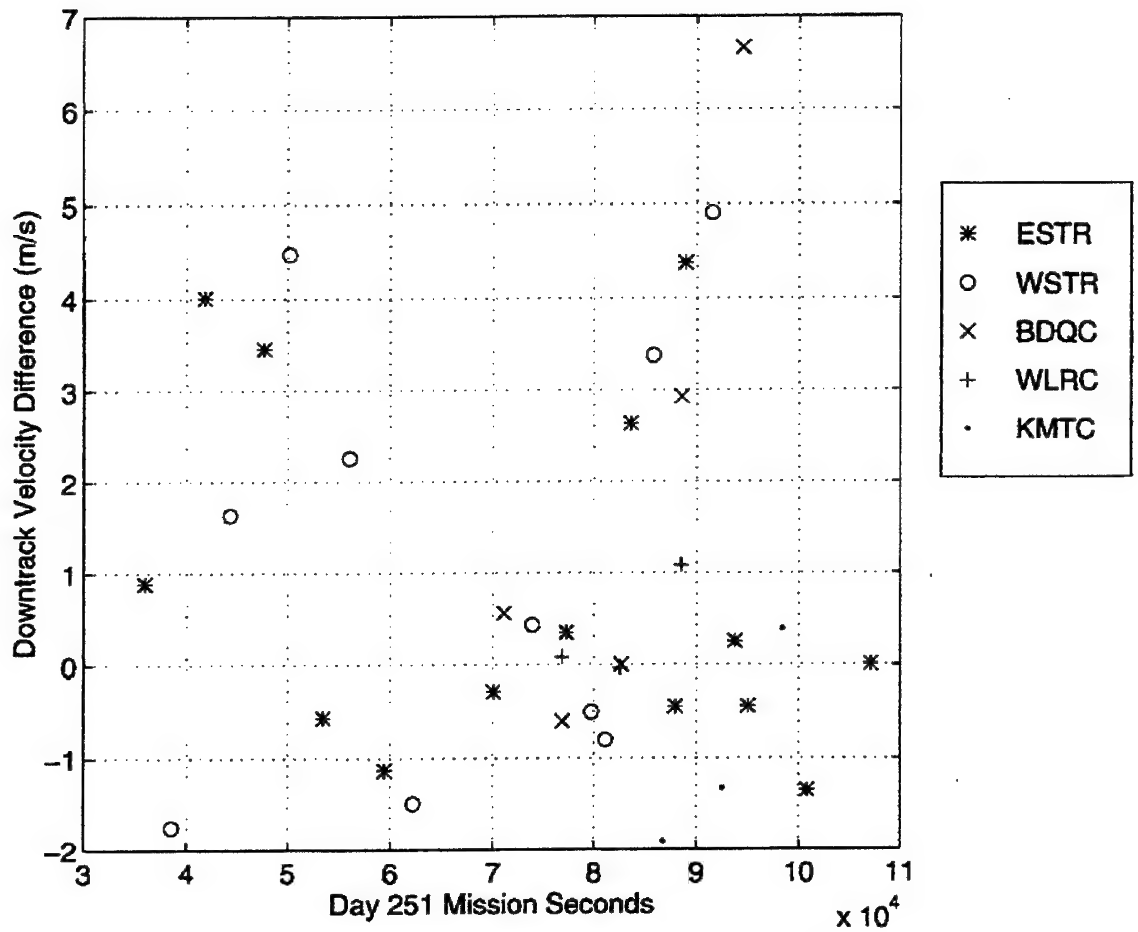


Figure 4.47. Day 251 Downtrack Velocity Difference.

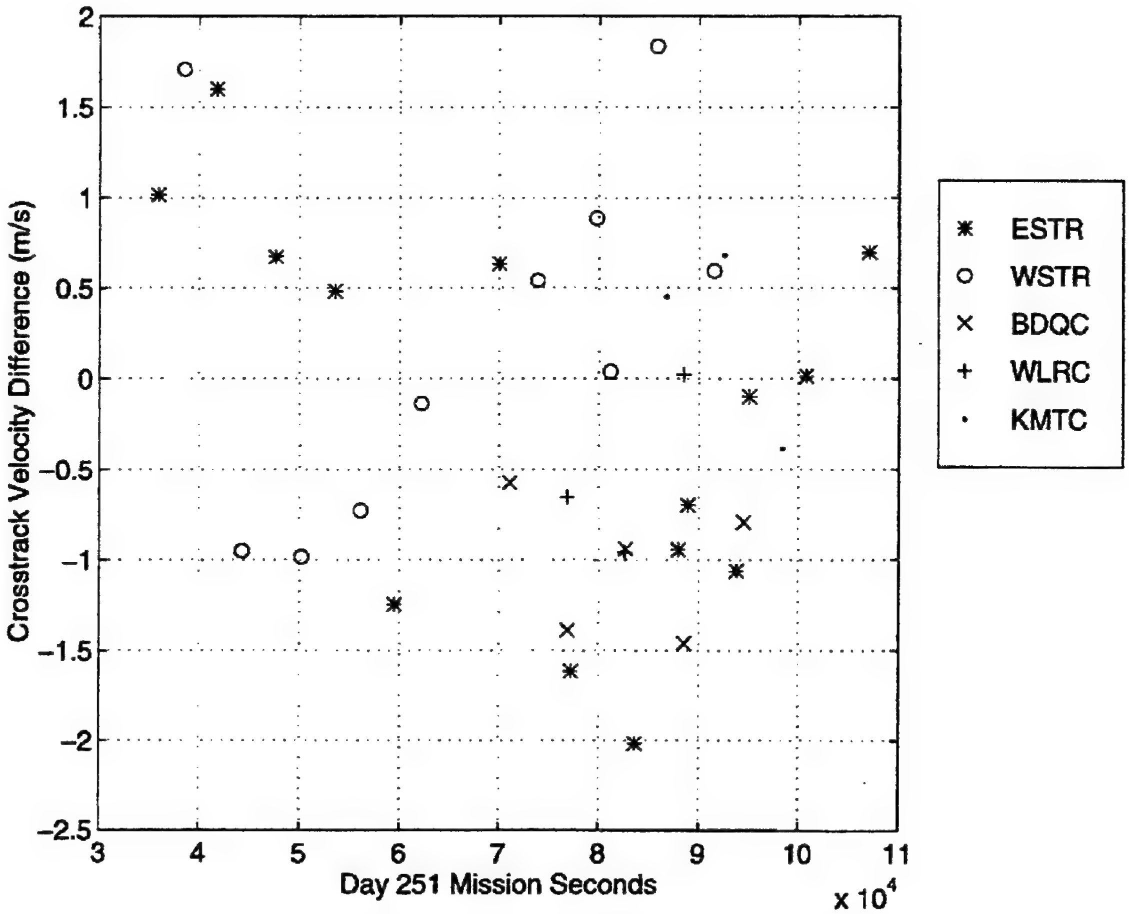


Figure 4.48. Day 251 Crosstrack Velocity Difference.

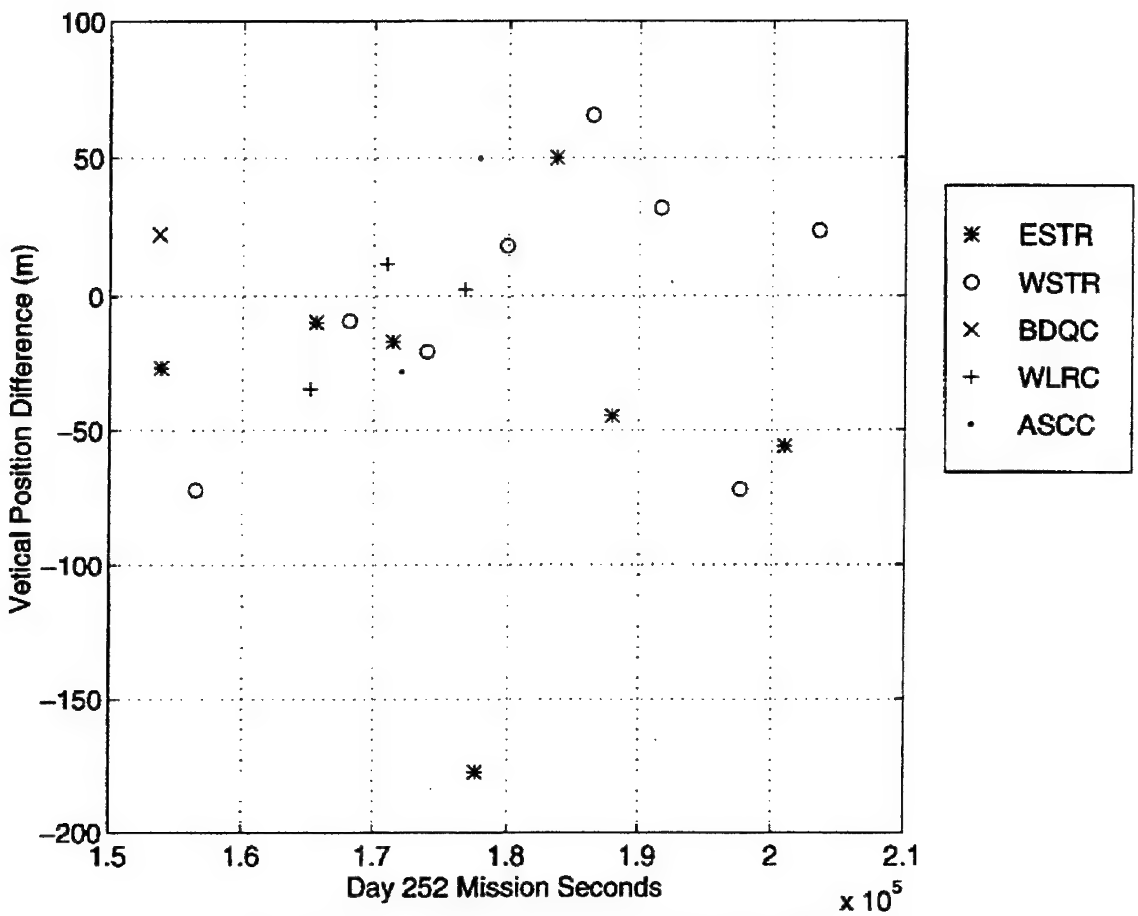


Figure 4.49. Day 252 Vertical Position Difference.

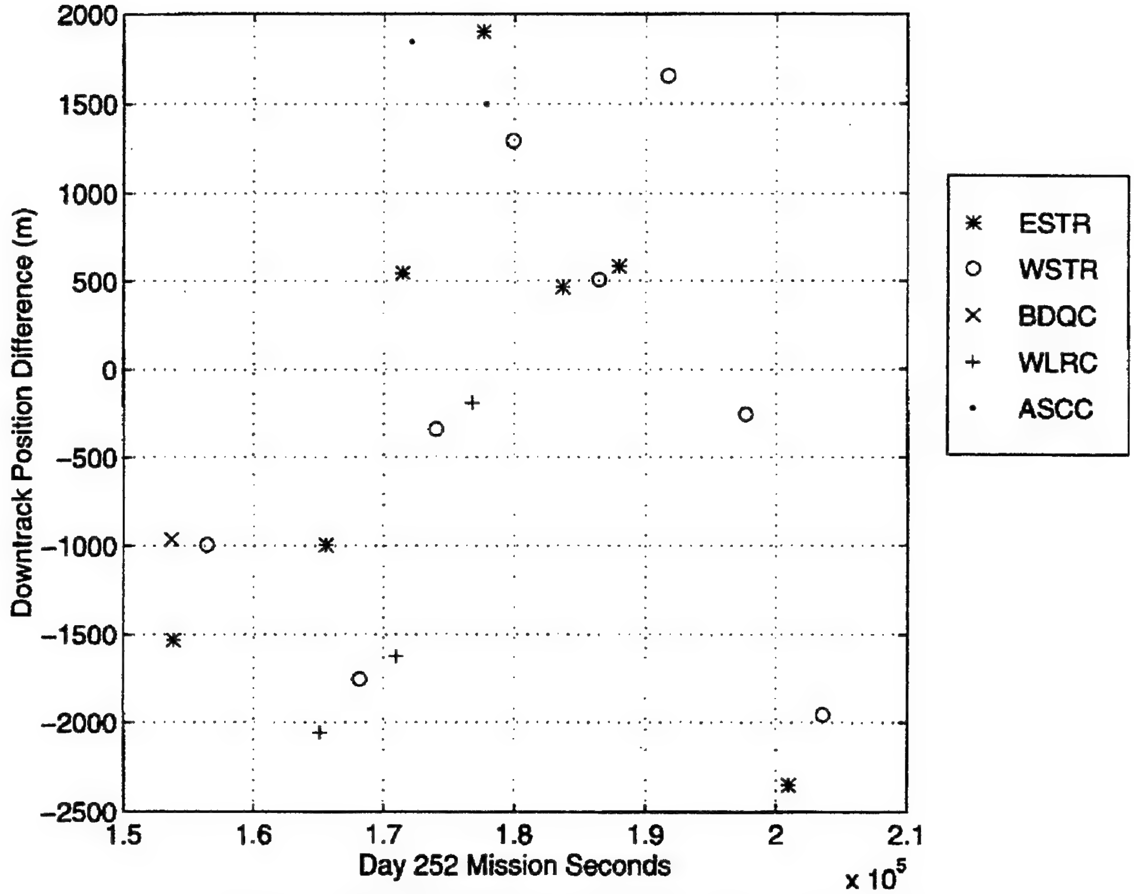


Figure 4.50. Day 252 Downtrack Position Difference.

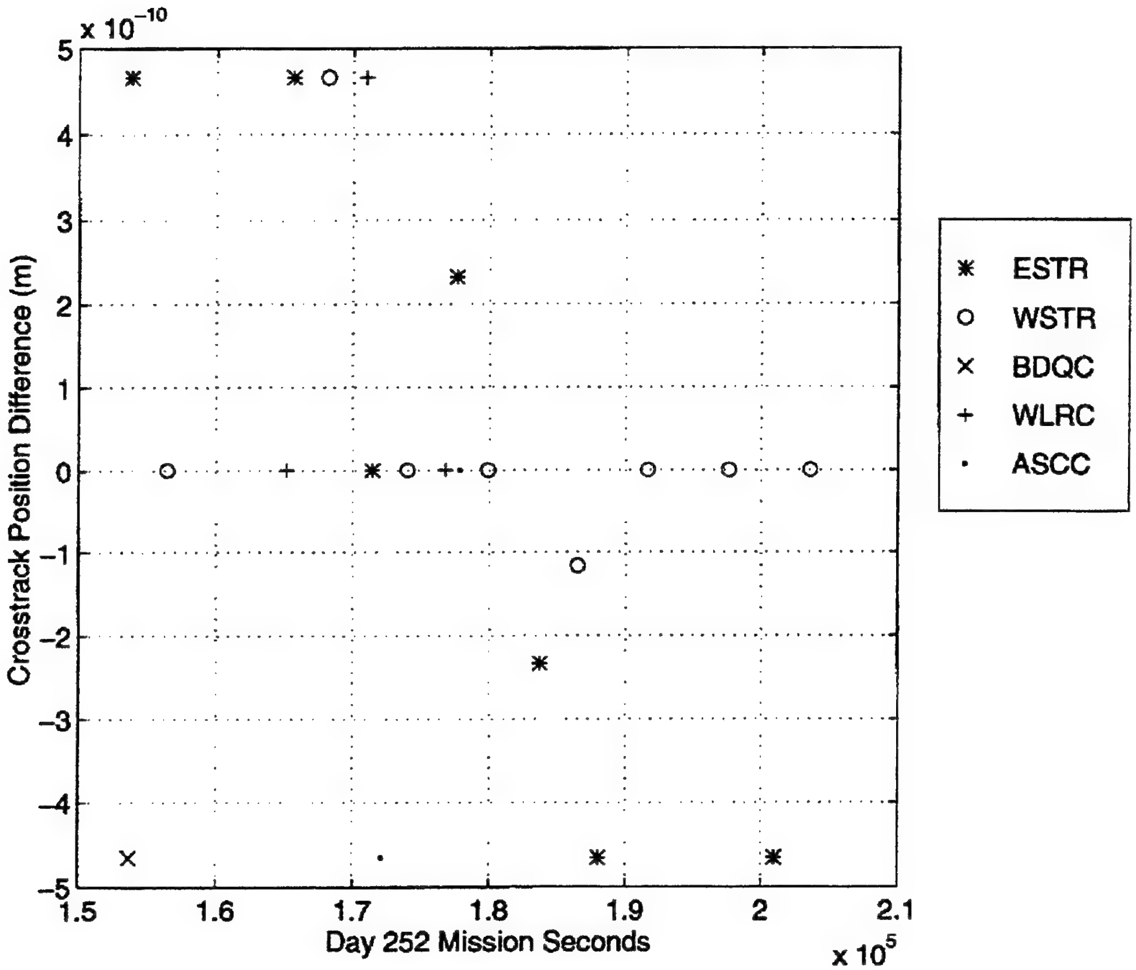


Figure 4.51. Day 252 Crosstrack Position Difference.

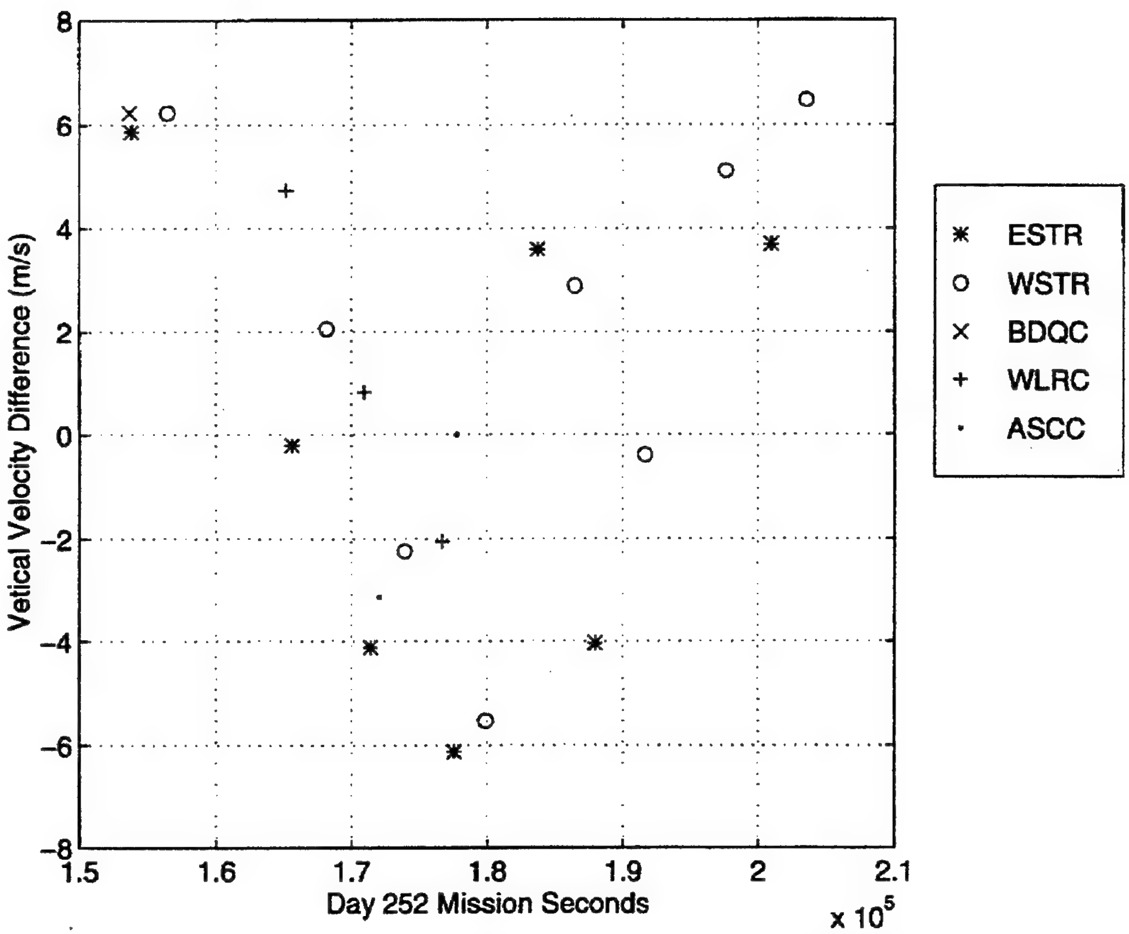


Figure 4.52. Day 252 Vertical Velocity Difference.

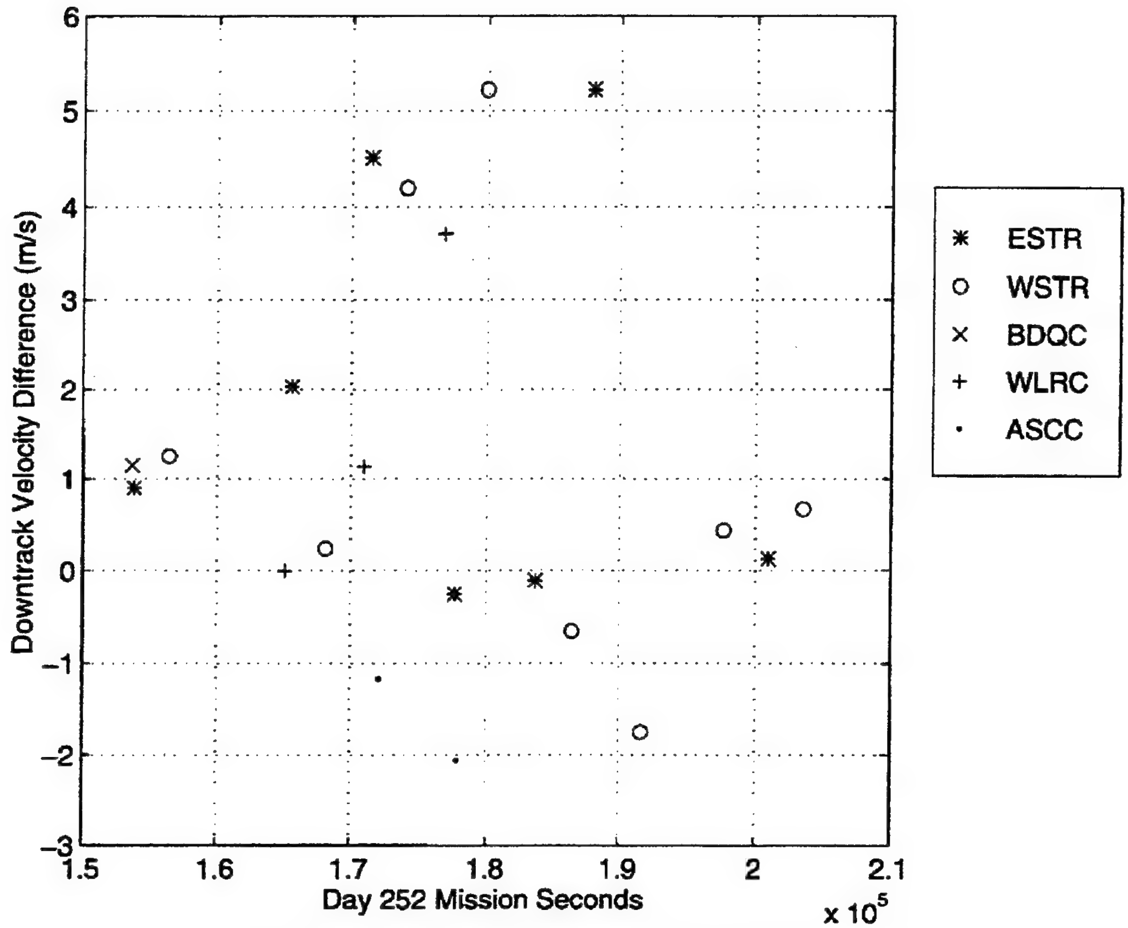


Figure 4.53. Day 252 Downtrack Velocity Difference.

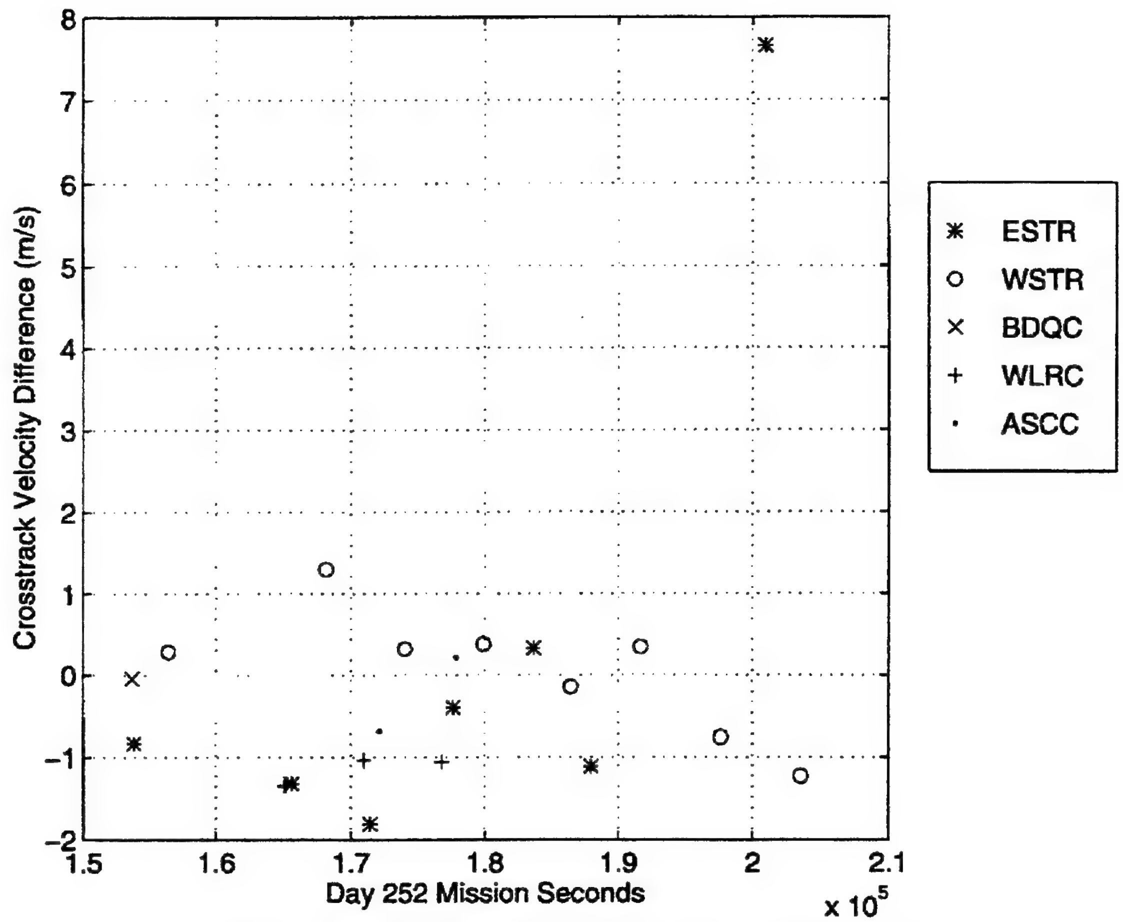


Figure 4.54. Day 252 Crosstrack Velocity Difference.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

GPS navigation solutions were available for approximately 65 percent of the STS-69 mission, and they generally coincided with the reference track. Based on vehicle track visualization using STK and based on conversion from J2000 coordinates to a spacecraft local UEN reference frame, differences between the GPS data and the reference data appear to have occurred predominantly in the downtrack direction. The fact that the two data sets were rounded to the nearest whole second probably impacted the downtrack differences between them significantly.

State vector differences between the GPS navigation solutions obtained using the Standard Positioning Service and the reference NAVG-11 state vectors for day 251 and 252 produced RMS position differences between the data sets of about 1500 m. One sigma position accuracy of 54 m in the vertical direction and approximately 1400 m in the downtrack direction were experienced. Velocity vector magnitude differences during this period were generally ± 1m/s, with a RMS velocity difference of less than 9 m/s. One sigma velocity accuracies of approximately 4.2 m/s in the vertical direction, 2.3 m/s in the downtrack direction and 1.5 m/s in the crosstrack direction were experienced. A firm conclusion regarding GPS accuracies could not be drawn because all sources of error were not identified.

GPS position and velocity data was generally very good; however, spurious data points were present. The errors included in these data points were sometimes very significant, and outages in GPS data of approximately two hours appeared to occur at least once per day. Despite these errors, GPS appeared to be effective in producing good state vector data even during vehicle maneuvers.

Based on these results GPS appears to be an excellent navigation source for providing Shuttle state vector information. Considering that this data can be obtained real-time and still match the reference so closely, real-time GPS state vector data appears even more valuable. An important caveat must be applied to this very valuable GPS data:

another navigation source such as INS must be present to provide a check against spurious data points and periods of outage.

B. RECOMMENDATIONS

Analysis of state vector data from a Precise Positioning Service GPS receiver should be conducted. PPS state vector data should provide considerably better position and velocity data which is required during rendezvous and proximity operations. STS-79 will provide an opportunity to assess PPS GPS receiver navigation solutions.

Before integration with the Shuttle navigation suite, experimentation with a simple filter for the GPS receiver navigation solutions is required. Erroneous GPS state vector data was sometimes quite severe. A process such as a Kalman filter is required to remove navigation solutions outside a specified tolerance.

A standard library of code in a commonly accepted language such as Fortran should be adopted for frequently required astronautical functions such as conversion between reference frames. In particular, a simple uniform routine for transformation between the J2000 ECI frame and the WGS-84 ECEF frame using general precession according to IAU-1976 and general nutation according to IAU-1980 without considering pole wander or the irregular rotation of the Earth is required. Algorithms which allow real time processing of data such as GPS navigation solutions should be emphasized. In contrast, current references emphasize the use of techniques which require post-flight processing due to their requirement of celestial observations.

GPS system time should be adopted by all tracking sources. Ambiguity caused by UTC being rounded to the nearest whole second by the GPS receiver and tracking sources led to significant errors, particularly in the downtrack direction. Since GPS system time can be obtained to a very high accuracy by both the Shuttle receiver and a receiver at the tracking site, GPS time would provide a valuable timescale addition to all tracking data sets.

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APPENDIX A. FORTRAN PROGRAM FOR EDITING PROPAGATED FILE

```
      program  edtprop

      implicit none                                   - declare variables
      double precision hours,xft,yft,zft,vxft,vyft,vzft
      double precision secs,x,y,z,vx,vy,vz
      integer i,count

      open(5,file='prop.out',status='old')            - open data file
      rewind(5)
      open(6,file='prop.m50',status='unknown')        - open new data file
      rewind(6)

      write(6,*) 1                                    - convertTool header to
                                                        transform to J2000
      count=0
      do 100 i=1,90000
         read (5,*,end=200) hours,xft,yft,zft,vxft,vyft,vzft    - read data

         secs=hours*3600.0                    - covert MET hours to seconds
         x=xft*0.3048                         - convert feet to meters
         y=yft*0.3048
         z=zft*0.3048
         vx=vxft*0.3048
         vy=vyft*0.3048
         vz=vzft*0.3048

         write(6,1) secs,x,y,z,vx,vy,vz       - write to new data file

         count=count+1
100   continue
200   continue

      close(5)
      close(6)

1     format(f16.6,6(2x,f16.6))
      end
```

APPENDIX B. FORTRAN PROGRAM FOR EDITING NAVG-11 STATE VECTOR FILE

```
      program  edtsv

      implicit none                                    - declare variables
      double precision station,xft,yft,zft,vxft,vyft,vzft
      double precision x,y,z,vx,vy,vz
      integer sv,doy,hr,min,sec
      integer year,dayoyear,month,dayomon,hour,minute,second
      integer tmission,secs
      integer i,count

      open(5,file='sv.edt',status='old')                     - open data file
      rewind(5)
      open(6,file='sv.m50',status='unknown')                 - open new data file
      rewind(6)

      year=1995                                        - data required for MET
      dayoyear=250                                       conversion
      month=09
      dayomon=07
      hour=15
      minute=9
      second=0

      tmission=dayoyear*24*3600+hour*3600+minute*60+second    - MET start

      write(*,1) 1                                     - convertTool header to
1     format(i1)                                         transform to J2000

      count=0

      do 100 i=1,90000
      read (5,*,end=200) station,sv,doy,hr,min,sec,          - read desired data
   %                       xft,yft,zft,vxft,vyft,vzft

            secs=(doy*24*3600+hr*3600+min*60+sec)-tmission   - MET conversion

            x=xft*0.3048                               - convert feet to meters
            y=yft*0.3048
            z=zft*0.3048
            vx=vxft*0.3048
            vy=vyft*0.3048
            vz=vzft*0.3048

            write(6,2) secs,x,y,z,vx,vy,vz             - write to new data file

       count=count+1
```

```
100         continue
200     continue

        close(5)
        close(6)

2       format(i7,6(2x,f16.6))
        end
```

APPENDIX C. STK VEHICLE FILE

stk.v.2.0

BEGIN Vehicle

Name	STS69gpsday1

BEGIN VehiclePath

BEGIN J4Perturbation

EphemEpoch	7 Sep 1995 15:09:00.000000
StartTime	7 Sep 1995 15:09:00.00
StopTime	19 Sep 1995 00:00:00.00
SemiMajorAxis	6748537.000000
AltitudeOfApogee	370400.000000
AltitudeOfPerigee	370400.000000
RadiusOfApogee	6748537.000000
RadiusOfPerigee	6748537.000000
PeriodOfOrbit	5517.284751
MeanMotion	0.001139
Inclination	28.500000
Eccentricity	0.000000000000
ArgOfPerigee	0.000000
LongAscenNode	-151.000000
RightAscension	249.528639
TrueAnomaly	0.000000
MeanAnomaly	0.000000
TimePastAscenNode	0.000000
TimePastPerigee	0.000000
TimeStep	60.000000
OrbitGranularity	0.000000
NumberOfPasses	0
SizeShapeType	AppPeriAlt
AscenNodeType	Longitude
AnomalyType	TrueAnomaly
EllipseType	Osculating

END J4Perturbation

BEGIN PassDefn

Break	Ascending
Latitude	0.000000
DisplayFlag	Both

```
    FirstPass                   1
    RangeFirstPass              0
    RangeLastPass               2147483647
    DisplayScheme               AllEphemeris
    ScenarioEpoch               1 Nov 1992 00:00:00.0
    Passes
    END Passes
END PassDefn

END VehiclePath

BEGIN Ephemeris

NumberOfEphemerisPoints         17342

ScenarioEpoch                   1 Nov 1992 00:00:00.0

EphemerisEcfTimePosVel

89944473.000000 -6290411.999970 -10669.639545 2444894.749963 -944.961651 -
7710.190409 -2382.491604
89944485.000000 -6300850.499989 -92193.726556 2416095.999986 -847.046094 -
7710.033323 -2420.407165
89944522.000000 -6325375.499997 -331401.656250 2329124.749954 -591.753766 -
7704.550020 -2514.460050
.
.
.
90020994.000000 -5868722.494942 883252.418377 3213828.661367 -1541.348168 -
7851.489098 -89.026636
90020994.000000 -5868722.494942 883252.418377 3213828.661367 -1541.348168 -
7851.489098 -89.026636
90020994.000000 -5868722.494942 883252.418377 3213828.661367 -1541.348168 -
7851.489098 -89.026636

END Ephemeris

BEGIN Attitude

  BEGIN ECFVVLH

     AZIMUTH          0.000000

  END ECFVVLH

END Attitude
```

```
BEGIN Swath

    ElevationAngle        0.000000
    HalfAngle             0.000000
    RepType               NoSwath

END Swath

BEGIN Constraints

    ConstraintMask           0
    MinRange                 0.000000
    MaxRange                 1000000000.000000
    MinAzimuthAngle          -90.000000
    MaxAzimuthAngle          180.000000
    MinElevationAngle        -45.000000
    MaxElevationAngle        45.000000
    MinGrazingAngle          0.000000
    MaxGrazingAngle          45.000000
    MinGrazingAltitude       185200.000000
    MaxGrazingAltitude       1852000.000000
    MinGndElevationAngle     0.000000
    MaxGndElevationAngle     90.000000
    MinSunElevationAngle     -90.000000
    MaxSunElevationAngle     90.000000
    LightingCondition        5

END Constraints

BEGIN Attributes

MarkerColor                          6
GroundTrackColor                     6
SwathColor                           6
LineStyle                            3
MarkerStyle                          4

END Attributes

BEGIN Graphics

    Inherit           On
    ShowLabel         On
    ShowGndTrack      On
```

```
END Graphics

BEGIN Extensions

  BEGIN Desc
  END Desc

  BEGIN Group
  END Group

  BEGIN Eclipse

    Penumbra            Off
    PenumbraColor       7
    PenumbraLineStyle   0
    PenumbraLineWidth   1


    Sunlight            Off
    SunlightColor       7
    SunlightLineStyle   0
    SunlightLineWidth   1

    Umbra               Off
    UmbraColor          7
    UmbraLineStyle      0
    UmbraLineWidth      1

  END Eclipse

  BEGIN Exclusion
  END Exclusion

END Extensions

BEGIN SubObjects

Class Sensor

          Horizon

END Class

END SubObjects

END Vehicle
```

APPENDIX D. MATLAB M-FILE FOR COMPARING GPS AND PROPAGATED DATA

```
% Program:  diffday1.m
% Jim Jones
% 25 May 96

% This program displays x,y and z components of GPS and reference
% track position and velocity data for one day of data.  It also
% displays the magnitude of the position vector, or altitude,
% from the center of the earth and the magnitude of the velocity
% vector.

% Load the GPS data file for one day

load gpsday1.j20 -ascii

gpsin=gpsday1;

% Create time, position component and velocity component vectors.

gpssec=gpsin(:,1);
gpsx=gpsin(:,2);
gpsy=gpsin(:,3);
gpsz=gpsin(:,4);
gpsxdot=gpsin(:,5);
gpsydot=gpsin(:,6);
gpszdot=gpsin(:,7);

% Load the reference track data file for one day

load propday1.j20 -ascii

propin=propday1;

% Create time, position component and velocity component vectors.

propsec=propin(:,1);
propx=propin(:,2);
propy=propin(:,3);
propz=propin(:,4);
propxdot=propin(:,5);
propydot=propin(:,6);
propzdot=propin(:,7);
```

```
% Plot position components vs. time

figure(1)
subplot(3,1,1)
plot(gpssec,gpsx,'w*',propsec,propx,'w')
xlabel('Day 251 Mission Seconds')
ylabel('X Position (m)')
grid


subplot(3,1,2)
plot(gpssec,gpsy,'w*',propsec,propy,'w')
xlabel('Day 251 Mission Seconds')
ylabel('Y Position (m)')
grid

subplot(3,1,3)
plot(gpssec,gpsz,'w*',propsec,propz,'w')
xlabel('Day 251 Mission Seconds')
ylabel('Z Position (m)')
tol=-1;
legend('GPS','Reference',tol)
grid
orient tall
%print_orig -dgif8 251pos.gif
print

% Plot velocity components vs. time

figure(2)
subplot(3,1,1)
plot(gpssec,gpsxdot,'w*',propsec,propxdot,'w')
xlabel('Day 251 Mission Seconds')
ylabel('X Velocity (m/s)')
grid

subplot(3,1,2)
plot(gpssec,gpsydot,'w*',propsec,propydot,'w')
xlabel('Day 251 Mission Seconds')
ylabel('Y Velocity (m/s)')
grid
```

```
subplot(3,1,3)
plot(gpssec,gpszdot,'w*',propsec,propzdot,'w')
xlabel('Day 251 Mission Seconds')
ylabel('Z Velocity (m/s)')
tol=-1;
legend('GPS','Reference',tol)
grid
orient tall
%print_orig -dgif8 251vel.gif
print

% Calculate position vector magnitudes (altitude)

gpsr=sqrt(gpsx.^2 + gpsy.^2 + gpsz.^2);
propr=sqrt(propx.^2 + propy.^2 + propz.^2);

% Calculate velocity vector magnitude

gpsv=sqrt(gpsxdot.^2 + gpsydot.^2 + gpszdot.^2);
propv=sqrt(propxdot.^2 + propydot.^2 + propzdot.^2);



% Plot position and velocity vector magnitudes

figure(3)
subplot(2,1,1)
plot(gpssec,gpsr,'w*',propsec,propr,'w')
xlabel('Day 251 Mission Seconds')
ylabel('Position Vector Magnitude (Vehicle Altitude) (m)')
tol=-1
legend('GPS','Reference',tol)
grid

subplot(2,1,2)
plot(gpssec,gpsv,'w*',propsec,propv,'w')
xlabel('Day 251 Mission Seconds')
ylabel('Velocity Vector Magnitude (m/s)')
tol=-1
legend('GPS','Reference',tol)
grid
orient tall
%print_orig -dgif8 251mag.gif
print

% Plot close up of position data
```

```
figure(4)
plot(gpssec,gpsx,'w*',propsec,propx,'wo')
xlabel('Day 251 Mission Seconds')
ylabel('X Position (m)')
tol=-1
legend('GPS','Reference',tol)
grid
axis([(5e4+20) (5e4+220) -0.57e7 -0.47e7])
%print_orig -dgif8 251close.gif
print
```

APPENDIX E. MATLAB M-FILE FOR PLOTTING GPS ORBIT IN 3-D

```
% Program:  orbplt1.m
% Jim Jones
% 25 May 96

% This program creates a 3D plot in J2000 coordinates of GPS navigation
% solutions for one day of flight data.

% Load GPS ephemeris file in X,Y,Z J2000 coordinates

load gpsday0.j20 -ascii

out = gpsday0;

% Plot ephemeris from data file

x1 = [0 1e7];
x2 = [0 0];
x3 = [0 0];

y1 = [0 0];
y2 = [0 1e7];
y3 = [0 0];

z1 = [0 0];
z2 = [0 0];
z3 = [0 1e7];

figure(1)
plot3(x1,x2,x3,'w-',y1,y2,y3,'w-',z1,z2,z3,'w-',out(:,2),out(:,3),out(:,4),'w.')
title('GPS Orbit for Day 250 in J2000 Coordinates')
xlabel('X Axis (m)')
ylabel('Y Axis (m)')
zlabel('Z Axis (m)')
%print_orig -dgif8 250orb.gif
print
```

APPENDIX F. MATLAB M-FILE FOR COMPARING GPS AND NAVG-11 STATE VECTORS WITH MATCHING TIMES

```
% Program:  diffmat1.m
% Jim Jones
% 25 May 96

% This program plots differences between GPS navigation solution
% data and Rockwell state vector data which share the same time.
% Both data sets are in J2000 coordinates.


% Load GPS data file

load gpsmatch1.j20 -ascii

gpsin=gpsmatch1;

% Create time, position component and velocity component vectors.

gpssec=gpsin(:,1);
gpsx=gpsin(:,2);
gpsy=gpsin(:,3);
gpsz=gpsin(:,4);
gpsxdot=gpsin(:,5);
gpsydot=gpsin(:,6);
gpszdot=gpsin(:,7);

% Load Rockwell state vector data

load svmatch1.j20 -ascii

propin=svmatch1;

% Create time, position component and velocity component vectors.

propsec=propin(:,1);
propx=propin(:,2);
propy=propin(:,3);
propz=propin(:,4);
propxdot=propin(:,5);
propydot=propin(:,6);
propzdot=propin(:,7);
```

```
% Identify sources of Rockwell state vectors
% (Sources corresponding to indices of matrix propin)
%                                                       Legend
estr=[1 3 5 7 9 11 16 21 24 27 30 32 34 36];           % *
wstr=[2 4 6 8 10 13 17 18 22 28       35 37];          % o
bdqc=[12 15 20 26 31];                                 % x
wlrc=[14 19 25];                                       % +
kmtc=[23 29 33];                                       % .


% Plot position components vs. time

figure(1)
subplot(3,1,1)
plot(gpssec,gpsx,'w*',propsec,propx,'wo')
xlabel('Day 251 Mission Seconds')
ylabel('X Position (m)')
grid

subplot(3,1,2)
plot(gpssec,gpsy,'w*',propsec,propy,'wo')
xlabel('Day 251 Mission Seconds')
ylabel('Y Position (m)')
grid

subplot(3,1,3)
plot(gpssec,gpsz,'w*',propsec,propz,'wo')
xlabel('Day 251 Mission Seconds')
ylabel('Z Position (m)')
tol=-1;
legend('GPS','Reference',tol)
grid
orient tall
%print_orig -dgif8 251posm.gif
print

% Plot velocity components vs. time

figure(2)
subplot(3,1,1)
plot(gpssec,gpsxdot,'w*',propsec,propxdot,'wo')
xlabel('Day 251 Mission Seconds')
ylabel('X Velocity (m/s)')
grid
```

```
subplot(3,1,2)
plot(gpssec,gpsydot,'w*',propsec,propydot,'wo')
xlabel('Day 251 Mission Seconds')
ylabel('Y Velocity (m/s)')
grid

subplot(3,1,3)
plot(gpssec,gpszdot,'w*',propsec,propzdot,'wo')
xlabel('Day 251 Mission Seconds')
ylabel('Z Velocity (m/s)')
tol=-1;
legend('GPS','Reference',tol)
grid
orient tall
%print_orig -dgif8 251velm.gif
print

% Calculate position vector magnitudes (altitude)

gpsr=sqrt(gpsx.^2 + gpsy.^2 + gpsz.^2);
propr=sqrt(propx.^2 + propy.^2 + propz.^2);

% Calculate velocity vector magnitude

gpsv=sqrt(gpsxdot.^2 + gpsydot.^2 + gpszdot.^2);
propv=sqrt(propxdot.^2 + propydot.^2 + propzdot.^2);


% Plot position vector and velocity magnitudes

figure(3)
subplot(2,1,1)
plot(gpssec,gpsr,'w*',propsec,propr,'wo')
xlabel('Day 251 Mission Seconds')
ylabel('Position Vector Magnitude (Vehicle Altitude) (m)')
grid

subplot(2,1,2)
plot(gpssec,gpsv,'w*',propsec,propv,'wo')
xlabel('Day 251 Mission Seconds')
ylabel('Velocity Vector Magnitude (m/s)')
tol=-1
legend('GPS','Reference',tol)
grid
orient tall
%print_orig -dgif8 251magm.gif
```

```
print

% Calculate position component differences

posdiffx=gpsx-propx;
posdiffy=gpsy-propy;
posdiffz=gpsz-propz;

% Plot position component differences

        % Data source legend

        % estr -  *
        % wstr -  o
        % bdqc -  x
        % wlrc -  +
        % kmtc -  .

figure(4)
plot(propsec(estr),posdiffx(estr),'w*',...
   propsec(wstr),posdiffx(wstr),'wo',propsec(bdqc),posdiffx(bdqc),'wx',...
   propsec(wlrc),posdiffx(wlrc),'w+',propsec(kmtc),posdiffx(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('X Position Difference (m)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
%print_orig -dgif8 251difxm.gif
print

figure(5)
plot(propsec(estr),posdiffy(estr),'w*',...
   propsec(wstr),posdiffy(wstr),'wo',propsec(bdqc),posdiffy(bdqc),'wx',...
   propsec(wlrc),posdiffy(wlrc),'w+',propsec(kmtc),posdiffy(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Y Position Difference (m)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
%print_orig -dgif8 251difym.gif
print
```

```
figure(6)
plot(propsec(estr),posdiffz(estr),'w*',...
    propsec(wstr),posdiffz(wstr),'wo',propsec(bdqc),posdiffz(bdqc),'wx',...
    propsec(wlrc),posdiffz(wlrc),'w+',propsec(kmtc),posdiffz(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Z Position Difference (m)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
%print_orig -dgif8 251difzm.gif
print


% Calculate velocity component differences

veldiffx=gpsxdot-propxdot;
veldiffy=gpsydot-propydot;
veldiffz=gpszdot-propzdot;

% Plot velocity component differences

figure(7)
plot(propsec(estr),veldiffx(estr),'w*',...
    propsec(wstr),veldiffx(wstr),'wo',propsec(bdqc),veldiffx(bdqc),'wx',...
    propsec(wlrc),veldiffx(wlrc),'w+',propsec(kmtc),veldiffx(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('X Velocity Difference (m/s)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
%print_orig -dgif8 251dfxdm.gif
print

figure(8)
plot(propsec(estr),veldiffy(estr),'w*',...
    propsec(wstr),veldiffy(wstr),'wo',propsec(bdqc),veldiffy(bdqc),'wx',...
    propsec(wlrc),veldiffy(wlrc),'w+',propsec(kmtc),veldiffy(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Y Velocity Difference (m/s)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
%print_orig -dgif8 251dfydm.gif
print
```

```
figure(9)
plot(propsec(estr),veldiffz(estr),'w*',...
    propsec(wstr),veldiffz(wstr),'wo',propsec(bdqc),veldiffz(bdqc),'wx',...
    propsec(wlrc),veldiffz(wlrc),'w+',propsec(kmtc),veldiffz(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Z Velocity Difference (m/s)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
%print_orig -dgif8 251dfzdm.gif
print


% Calculate position and velocity magnitude differences

diffr=gpsr-propr;

diffv=gpsv-propv;

% Plot position and velocity magnitude differences

figure(10)
plot(propsec(estr),diffr(estr),'w*',...
    propsec(wstr),diffr(wstr),'wo',propsec(bdqc),diffr(bdqc),'wx',...
    propsec(wlrc),diffr(wlrc),'w+',propsec(kmtc),diffr(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Position Vector Magnitude (Altitude) Difference (m)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
%print_orig -dgif8 251difrm.gif
print

figure(11)
plot(propsec(estr),diffv(estr),'w*',...
    propsec(wstr),diffv(wstr),'wo',propsec(bdqc),diffv(bdqc),'wx',...
    propsec(wlrc),diffv(wlrc),'w+',propsec(kmtc),diffv(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Velocity Vector Magnitude Difference (m/s)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
%print_orig -dgif8 251difvm.gif
print
```

```
% Calculate position and velocity RMS differences

rmsr=sqrt(posdiffx.^2 + posdiffy.^2 + posdiffz.^2);

rmsv=sqrt(veldiffx.^2 + veldiffy.^2 + veldiffy.^2);

% Plot position and velocity RMS differences

figure(12)
plot(propsec(estr),rmsr(estr),'w*',...
    propsec(wstr),rmsr(wstr),'wo',propsec(bdqc),rmsr(bdqc),'wx',...
    propsec(wlrc),rmsr(wlrc),'w+',propsec(kmtc),rmsr(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Position RMS Difference (m)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
%print_orig -dgif8 251drmsm.gif
print

figure(13)
plot(propsec(estr),rmsv(estr),'w*',...
    propsec(wstr),rmsv(wstr),'wo',propsec(bdqc),rmsv(bdqc),'wx',...
    propsec(wlrc),rmsv(wlrc),'w+',propsec(kmtc),rmsv(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Velocity RMS Difference (m/s)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
%print_orig -dgif8 251dvmsm.gif
print
```

APPENDIX G. MATLAB M-FILE FOR TRANSFORMING MATCHING GPS AND NAVG-11 STATE VECTORS TO UEN FRAME FOR COMPARISON

```
% Program: uen251.m
% Jim Jones
% 25 June 96

% This program plots differences between GPS navigation solution
% data and NAVG-11 state vector data which share the same time.
% Both data sets are in the Shuttle UEN frame.

% Load the GPS data file for one day

load gpsmatch1.j20 -ascii

gpsin=gpsmatch1;

% Create time, position component and velocity component vectors.

gpssec=gpsin(:,1);
gpsx=gpsin(:,2);
gpsy=gpsin(:,3);
gpsz=gpsin(:,4);
gpsxdot=gpsin(:,5);
gpsydot=gpsin(:,6);
gpszdot=gpsin(:,7);

% Load the reference track data file for one day

load svmatch1.j20 -ascii

svin=svmatch1;

% Create time, position component and velocity component vectors.

refsec=svin(:,1);
refx=svin(:,2);
refy=svin(:,3);
refz=svin(:,4);
refxdot=svin(:,5);
refydot=svin(:,6);
refzdot=svin(:,7);
```

```
% Identify sources of NAVG-11 state vectors
% (Sources corresponding to indices of matrix svin)
%                                                   Legend
estr=[1 3 5 7 9 11 16 21 24 27 30 32 34 36];% *
wstr=[2 4 6 8 10 13 17 18 22 28];           % o
bdqc=[12 15 20 26 31];                      % x
wlrc=[14 19 25];                            % +
kmtc=[23 29 33];                            % .


for i=1:length(gpsx)

%       Elements required to calculate DCM for GPS data

        gpsR=sqrt(gpsx(i)^2+gpsy(i)^2+gpsz(i)^2);
        gpsgamma=atan2(gpsy(i),gpsx(i));
        gpsd=sqrt(gpsx(i)^2+gpsy(i)^2);
        gpsdelta=atan2(gpsz(i),gpsd);

%       DCM components for GPS data

        gpsdcm11=cos(gpsdelta)*cos(gpsgamma);
        gpsdcm12=cos(gpsdelta)*sin(gpsgamma);
        gpsdcm13=sin(gpsdelta);

        gpsdcm21=sin(gpsdelta);
        gpsdcm22=cos(gpsgamma);
        gpsdcm23=0;

        gpsdcm31=-sin(gpsdelta)*cos(gpsgamma);
        gpsdcm32=-sin(gpsdelta)*sin(gpsgamma);
        gpsdcm33=cos(gpsdelta);

%       DCM rows for GPS data

        gpsdcm1=[gpsdcm11 gpsdcm12 gpsdcm13];
        gpsdcm2=[gpsdcm21 gpsdcm22 gpsdcm23];
        gpsdcm3=[gpsdcm31 gpsdcm32 gpsdcm33];

%       3x3 DCM for GPS data

        gpsdcm=[gpsdcm1; gpsdcm2; gpsdcm3];
```

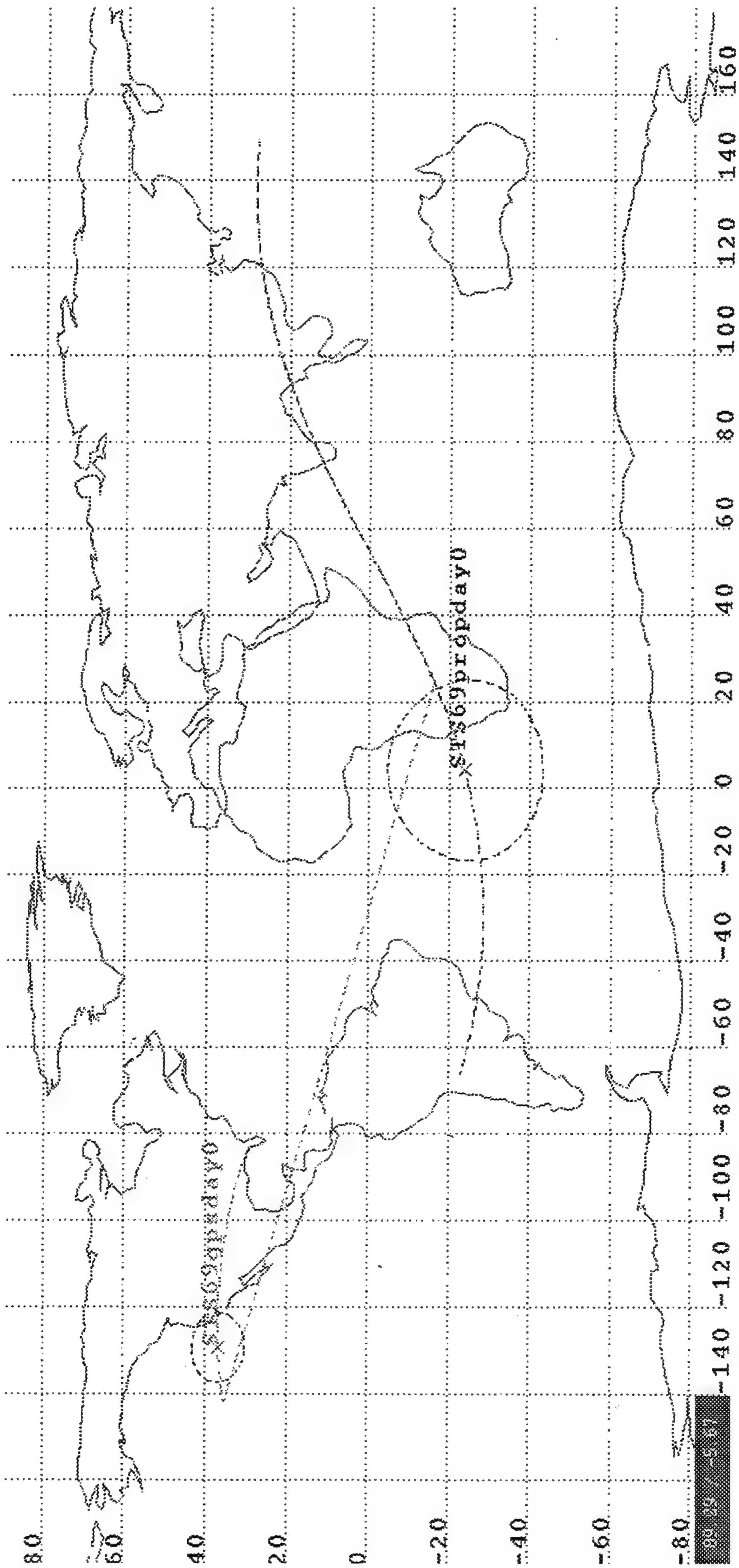
```
%       Create GPS position and velocity vectors

        gpspos=[gpsx(i); gpsy(i); gpsz(i)];
        gpsvel=[gpsxdot(i); gpsydot(i); gpszdot(i)];

%       Perform transformation from J2000 coordinates to UEN

        gpsuenp=gpsdcm*gpspos;
        gpsuenv=gpsdcm*gpsvel;

%       Elements required to calculate DCM for reference data

        refR=sqrt(refx(i)^2+refy(i)^2+refz(i)^2);
        refgamma=atan2(refy(i),refx(i));
        refd=sqrt(refx(i)^2+refy(i)^2);
        refdelta=atan2(refz(i),refd);

%       DCM components for reference data

        refdcm11=cos(refdelta)*cos(refgamma);
        refdcm12=cos(refdelta)*sin(refgamma);
        refdcm13=sin(refdelta);

        refdcm21=sin(refdelta);
        refdcm22=cos(refgamma);
        refdcm23=0;

        refdcm31=-sin(refdelta)*cos(refgamma);
        refdcm32=-sin(refdelta)*sin(refgamma);
        refdcm33=cos(refdelta);

%       DCM rows for reference data

        refdcm1=[refdcm11 refdcm12 refdcm13];
        refdcm2=[refdcm21 refdcm22 refdcm23];
        refdcm3=[refdcm31 refdcm32 refdcm33];

%       3x3 DCM for reference data

        refdcm=[refdcm1; refdcm2; refdcm3];

%       Create reference position and velocity vectors

        refpos=[refx(i); refy(i); refz(i)];
        refvel=[refxdot(i); refydot(i); refzdot(i)];
```

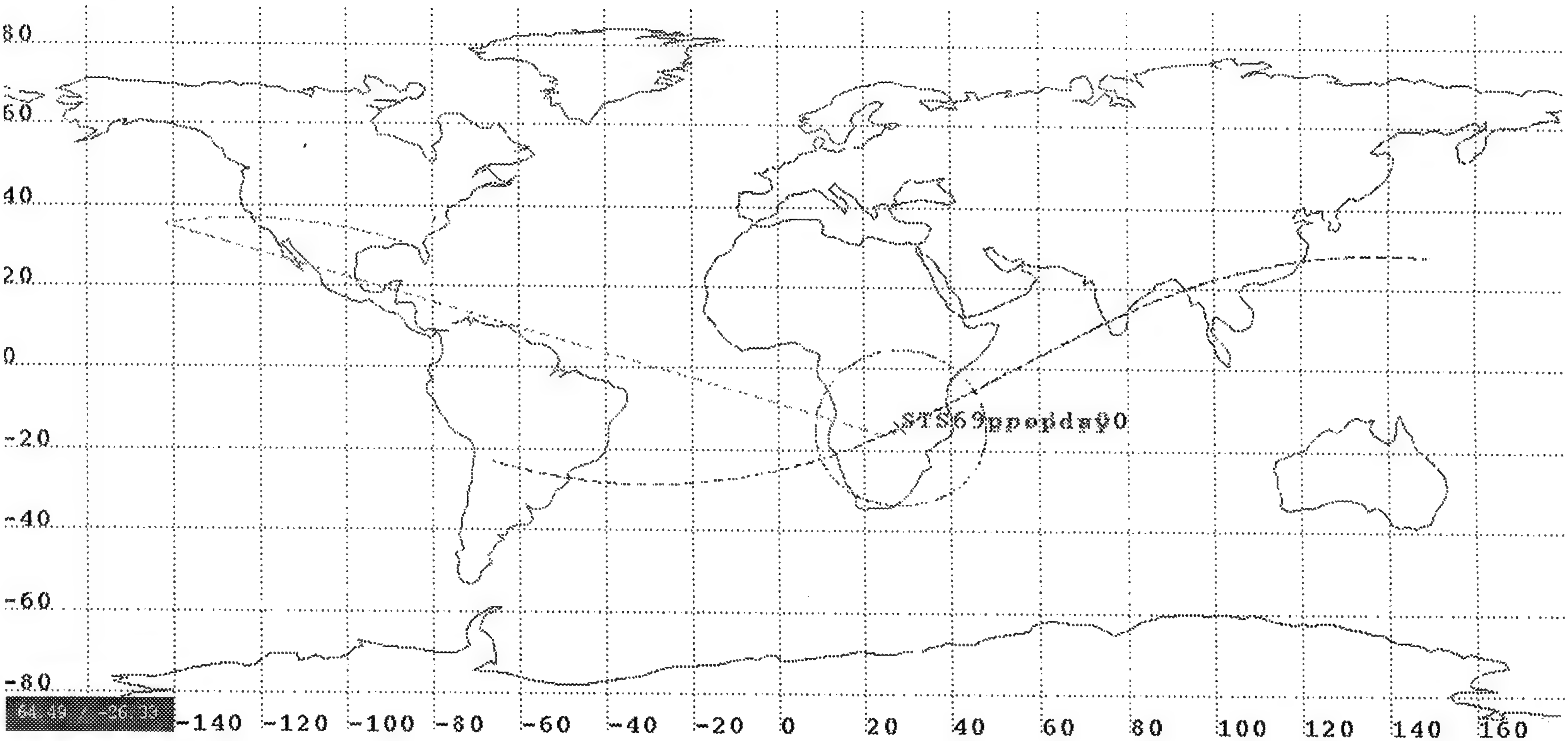
```
%       Perform transformation from J2000 coordinates to UEN

        refuenp=refdcm*refpos;
        refuenv=refdcm*refvel;

%       Calculate state vector differences

        difp=gpsuenp-refuenp;
        difv=gpsuenv-refuenv;

        vertp(i)=difp(1);
        dtrkp(i)=difp(2);
        xtrkp(i)=difp(3);

        vertv(i)=difv(1);
        dtrkv(i)=difv(2);
        xtrkv(i)=difv(3);

end

% Calculate average differences

vertpavg=mean(vertp);
dtrkpavg=mean(dtrkp);
xtrkpavg=mean(xtrkp);

vertvavg=mean(vertv);
dtrkvavg=mean(dtrkv);
xtrkvavg=mean(xtrkv);

% Calculate median differences

vertpmed=median(vertp);
dtrkpmed=median(dtrkp);
xtrkpmed=median(xtrkp);

vertvmed=median(vertv);
dtrkvmed=median(dtrkv);
xtrkvmed=median(xtrkv);
```

```
% Calculate standard deviations of differences

vertpstd=std(vertp);
dtrkpstd=std(dtrkp);
xtrkpstd=std(xtrkp);

vertvstd=std(vertv);
dtrkvstd=std(dtrkv);
xtrkvstd=std(xtrkv);

% Plot position component differences

figure(1)
plot(gpssec(estr),vertp(estr),'w*',gpssec(wstr),vertp(wstr),'wo',...
    gpssec(bdqc),vertp(bdqc),'wx',gpssec(wlrc),vertp(wlrc),'w+',...
    gpssec(kmtc),vertp(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Vetical Position Difference (m)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
print

figure(2)
plot(gpssec(estr),dtrkp(estr),'w*',gpssec(wstr),dtrkp(wstr),'wo',...
    gpssec(bdqc),dtrkp(bdqc),'wx',gpssec(wlrc),dtrkp(wlrc),'w+',...
    gpssec(kmtc),dtrkp(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Downtrack Position Difference (m)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
print

figure(3)
plot(gpssec(estr),xtrkp(estr),'w*',gpssec(wstr),xtrkp(wstr),'wo',...
    gpssec(bdqc),xtrkp(bdqc),'wx',gpssec(wlrc),xtrkp(wlrc),'w+',...
    gpssec(kmtc),xtrkp(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Crosstrack Position Difference (m)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
print
```

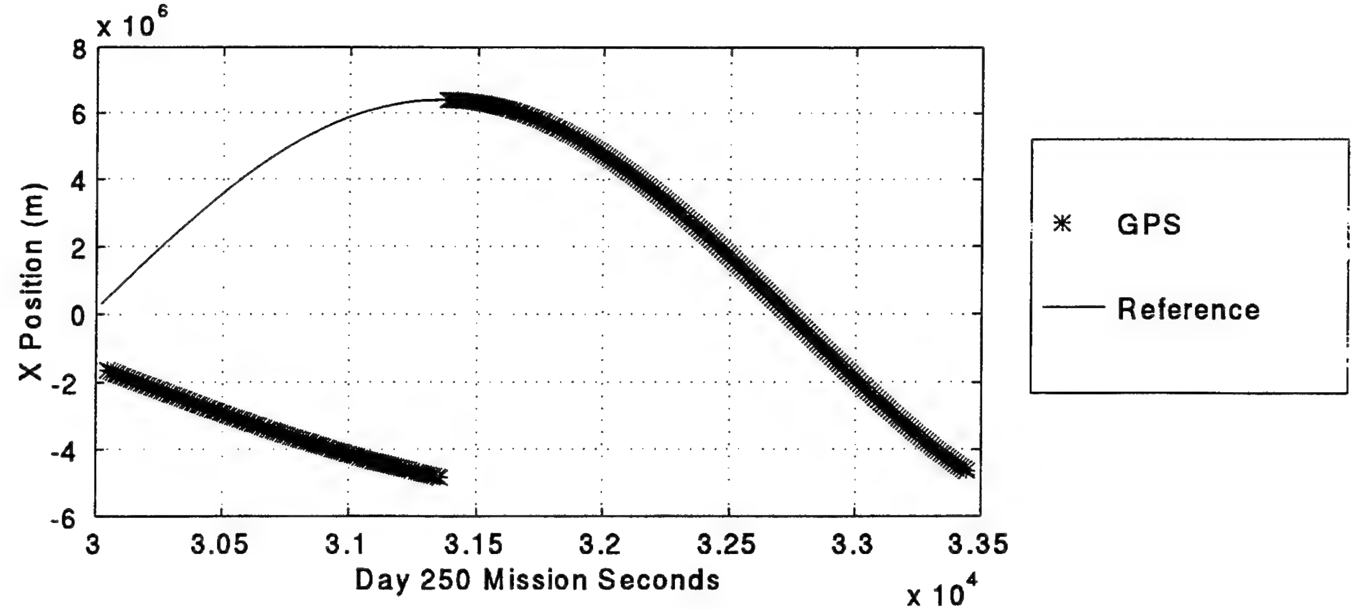
```
% Plot velocity component differences

figure(4)
plot(gpssec(estr),vertv(estr),'w*',gpssec(wstr),vertv(wstr),'wo',...
    gpssec(bdqc),vertv(bdqc),'wx',gpssec(wlrc),vertv(wlrc),'w+',...
    gpssec(kmtc),vertv(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Vetical Velocity Difference (m/s)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
print

figure(5)
plot(gpssec(estr),dtrkv(estr),'w*',gpssec(wstr),dtrkv(wstr),'wo',...
    gpssec(bdqc),dtrkv(bdqc),'wx',gpssec(wlrc),dtrkv(wlrc),'w+',...
    gpssec(kmtc),dtrkv(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Downtrack Velocity Difference (m/s)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
print

figure(6)
plot(gpssec(estr),xtrkv(estr),'w*',gpssec(wstr),xtrkv(wstr),'wo',...
    gpssec(bdqc),xtrkv(bdqc),'wx',gpssec(wlrc),xtrkv(wlrc),'w+',...
    gpssec(kmtc),xtrkv(kmtc),'w.')
xlabel('Day 251 Mission Seconds')
ylabel('Crosstrack Velocity Difference (m/s)')
grid
tol=-1;
legend('ESTR','WSTR','BDQC','WLRC','KMTC',tol)
print
```

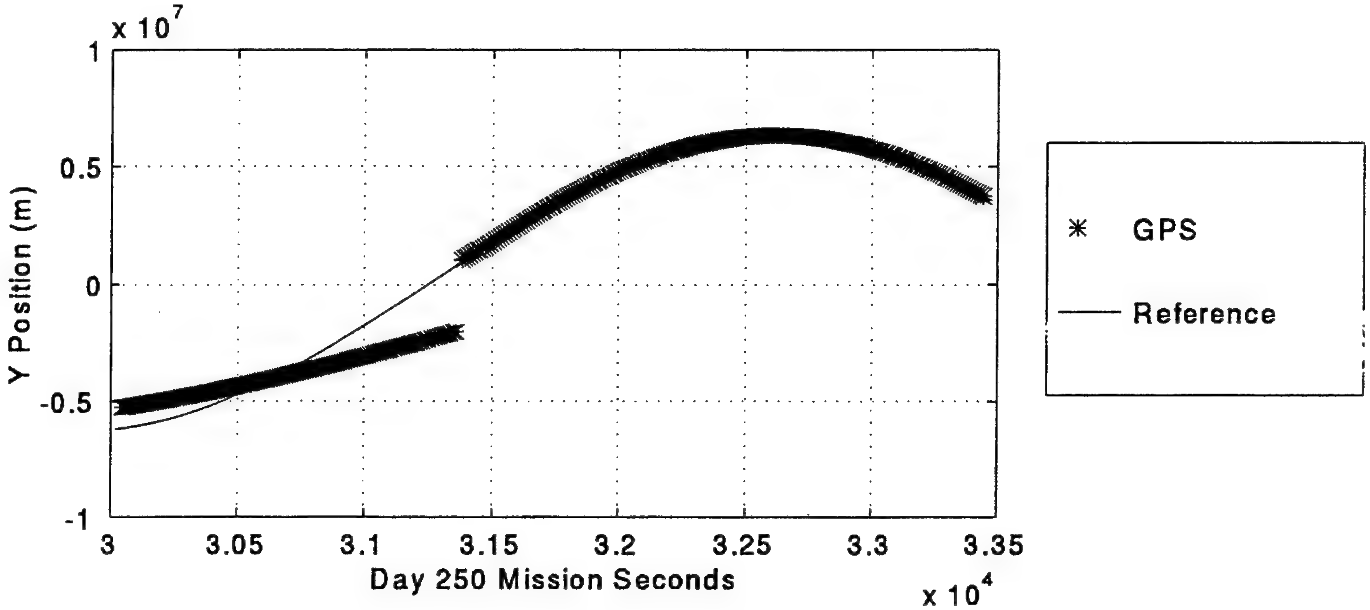
APPENDIX H. DAY 250 STK PLOTS

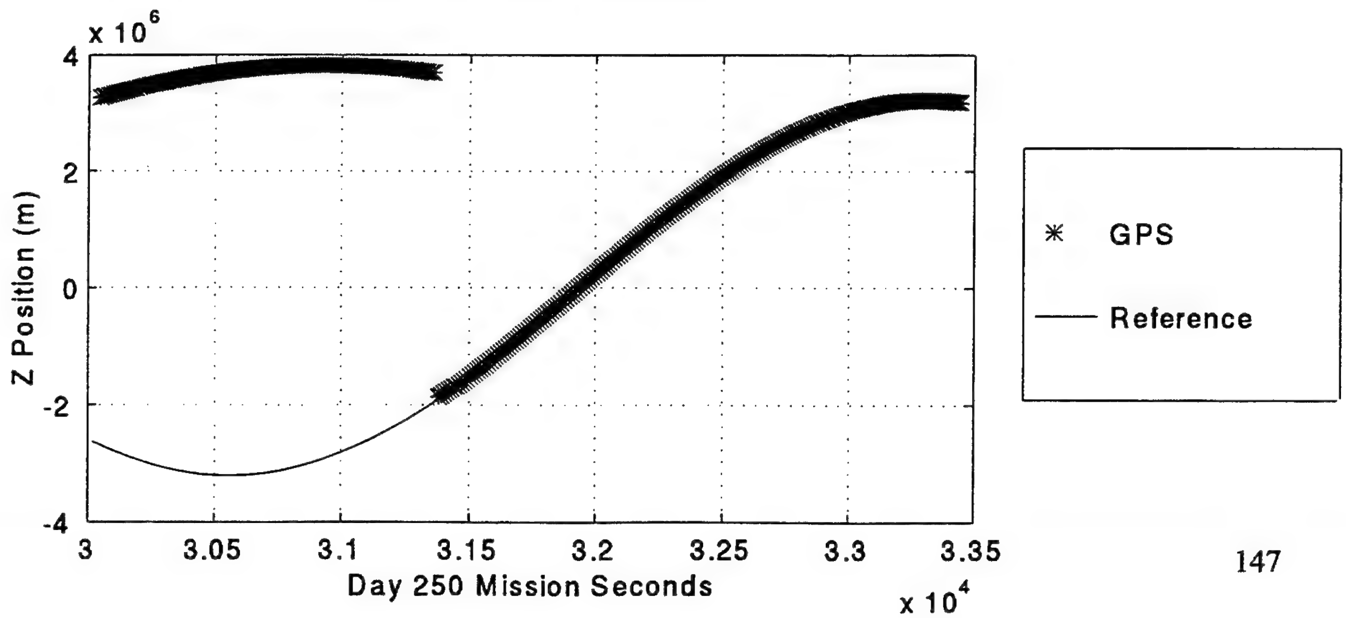

80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

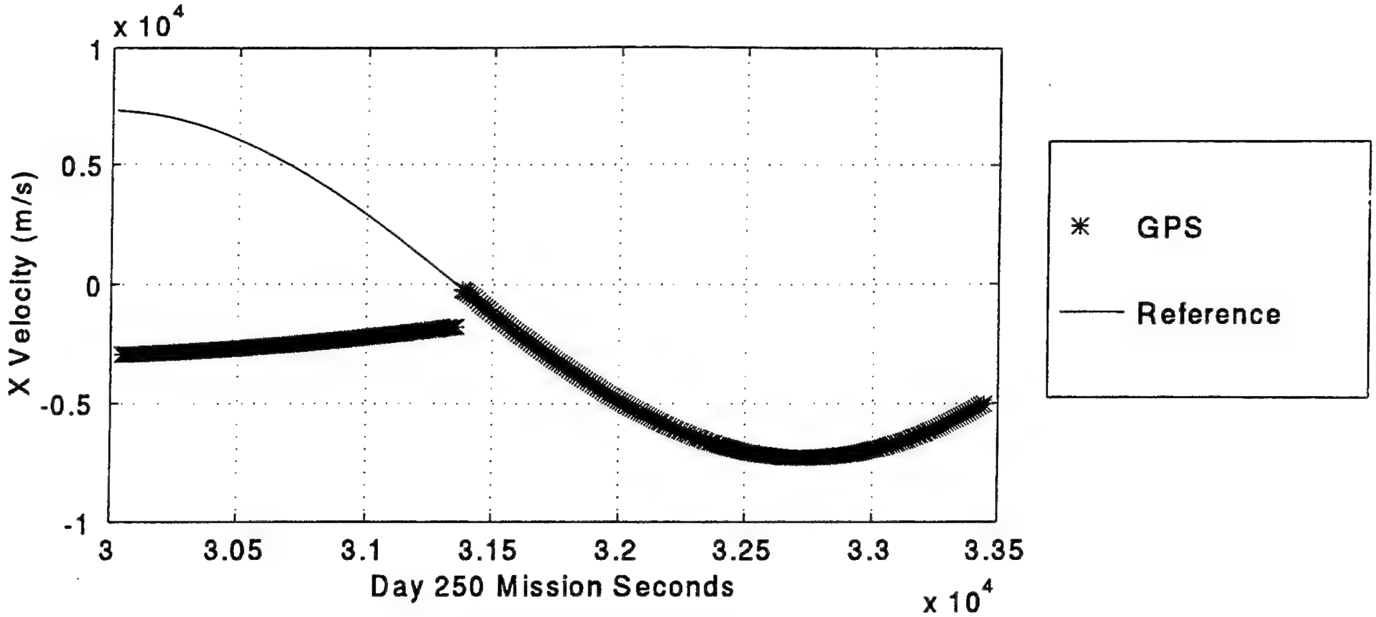

80
60
40
20
0
-20
-40
-60
-80
-140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160
STS69

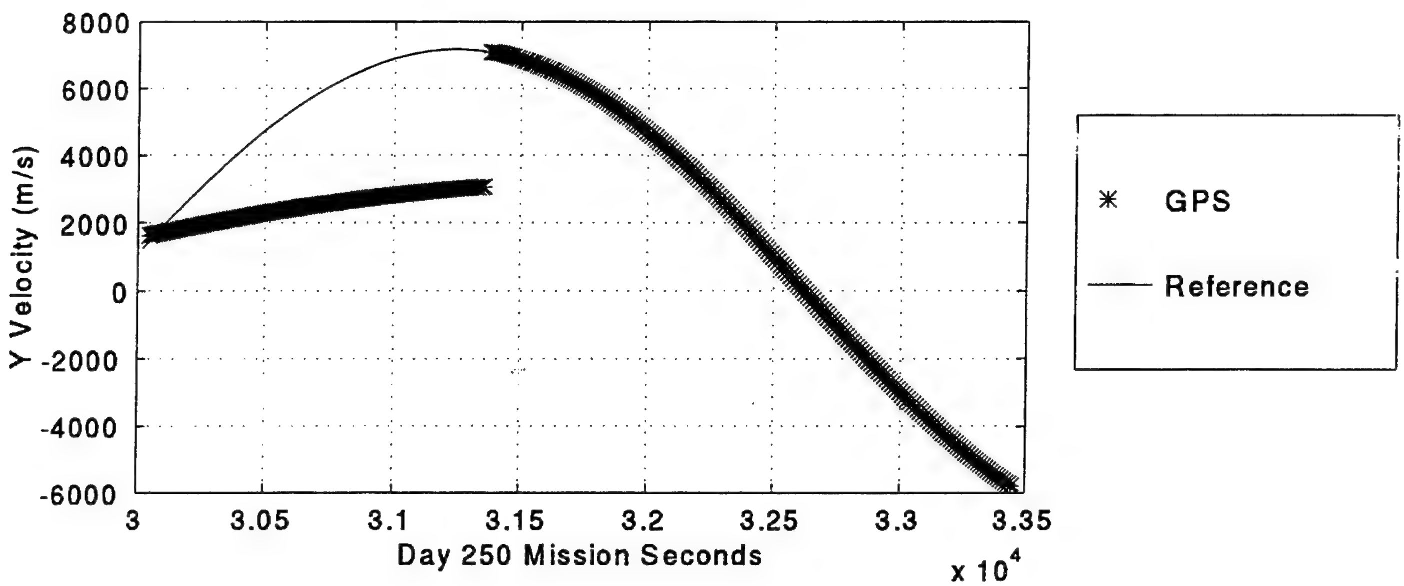
APPENDIX I. DAY 250 MATLAB PLOTS

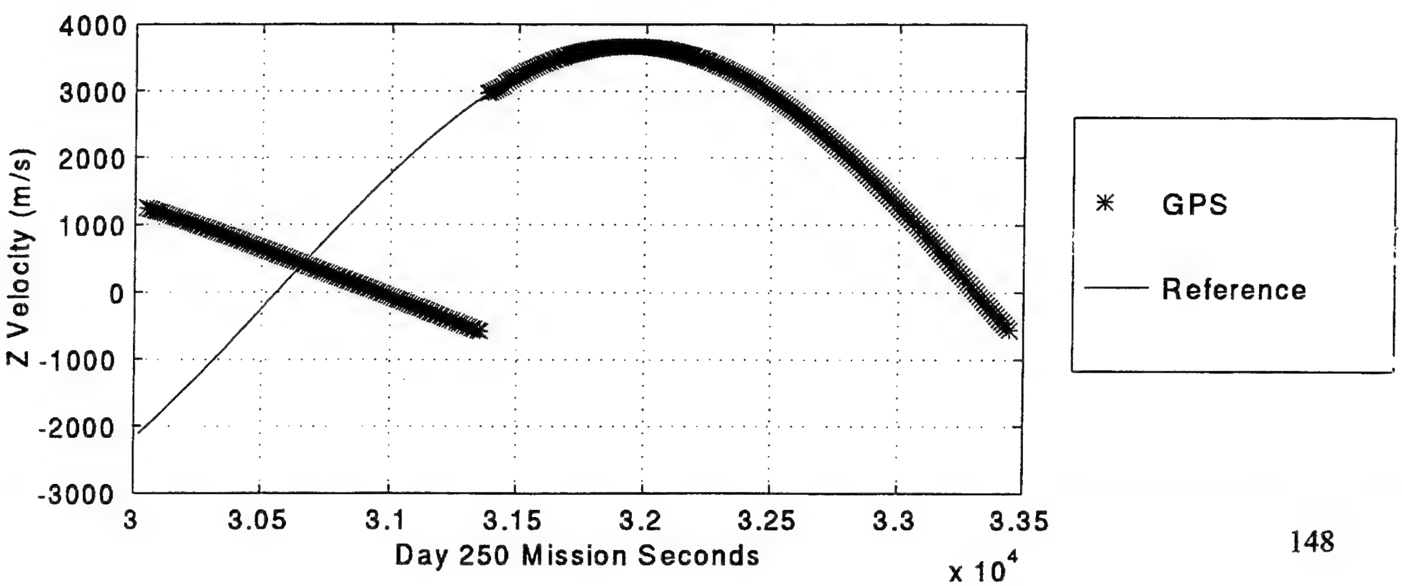

x 10^6
8
6
4
2
0
-2
-4
-6
X Position (m)
3
3.05
3.1
3.15
3.2
3.25
3.3
3.35
Day 250 Mission Seconds
x 10^4
GPS
Reference

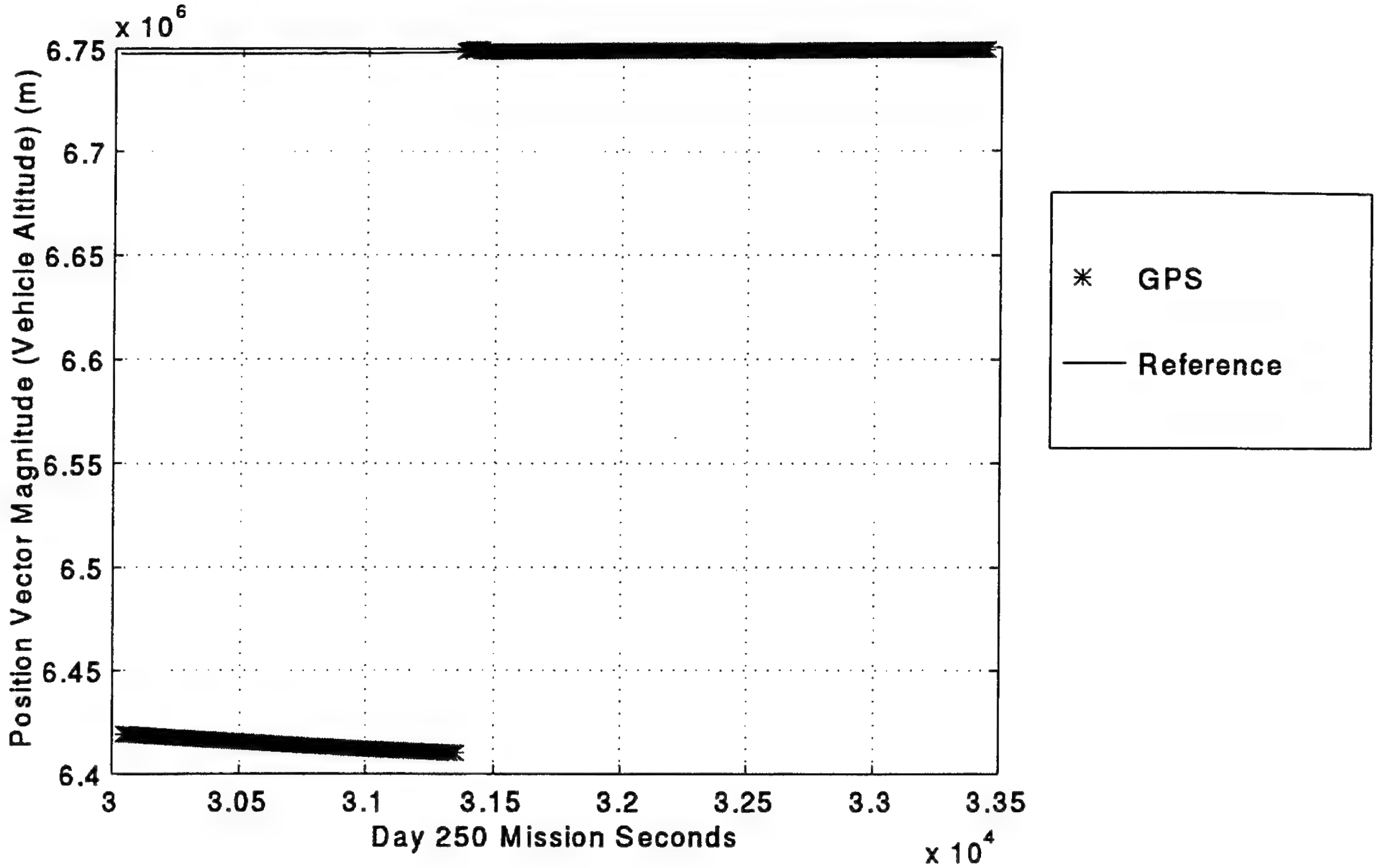

x 10^7
1
0.5
0
-0.5
-1
Y Position (m)
3
3.05
3.1
3.15
3.2
3.25
3.3
3.35
Day 250 Mission Seconds
x 10^4
GPS
Reference

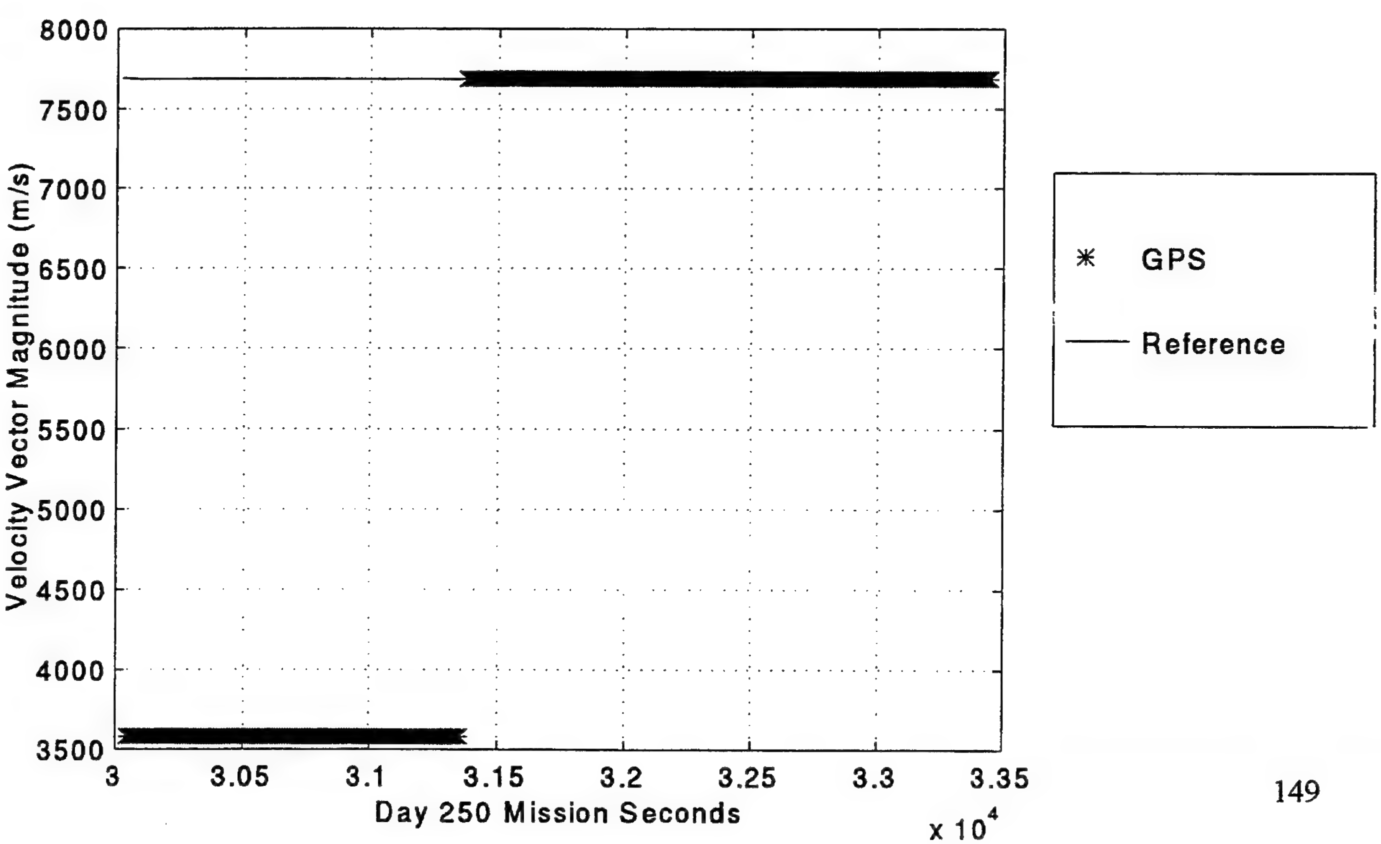

x 10^6
4
2
0
-2
-4
Z Position (m)
3
3.05
3.1
3.15
3.2
3.25
3.3
3.35
Day 250 Mission Seconds
x 10^4
GPS
Reference


x 10^4
1
0.5
0
-0.5
-1
X Velocity (m/s)
3
3.05
3.1
3.15
3.2
3.25
3.3
3.35
Day 250 Mission Seconds
x 10^4
GPS
Reference

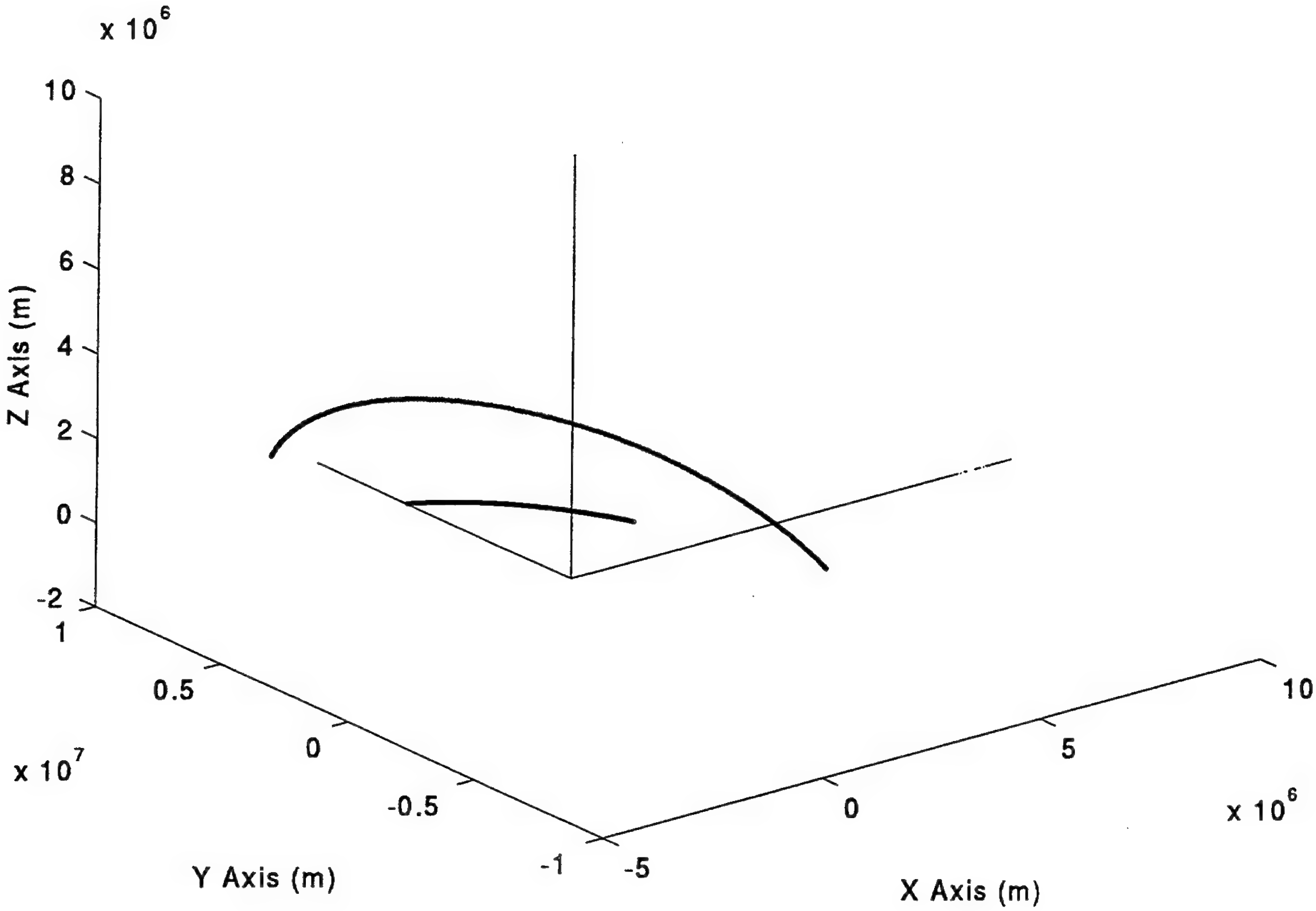

8000
6000
4000
2000
0
-2000
-4000
-6000
Y Velocity (m/s)
3
3.05
3.1
3.15
3.2
3.25
3.3
3.35
Day 250 Mission Seconds
x 10^4
GPS
Reference


4000
3000
2000
1000
0
-1000
-2000
-3000
Z Velocity (m/s)
3
3.05
3.1
3.15
3.2
3.25
3.3
3.35
Day 250 Mission Seconds
x 10^4
GPS
Reference

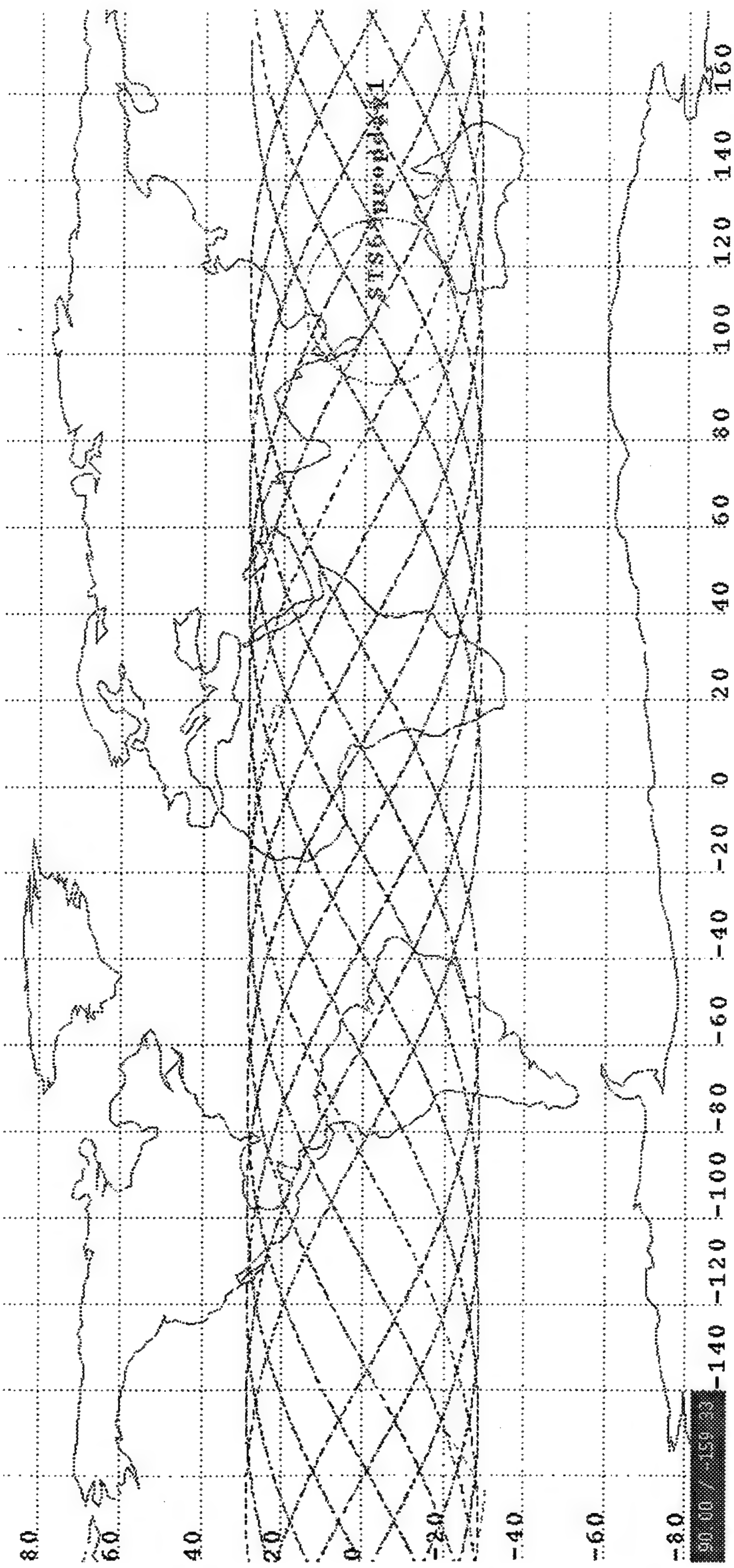

x 10^6
6.75
6.7
6.65
6.6
6.55
6.5
6.45
6.4
Position Vector Magnitude (Vehicle Altitude) (m)
3
3.05
3.1
3.15
3.2
3.25
3.3
3.35
Day 250 Mission Seconds
x 10^4
GPS
Reference

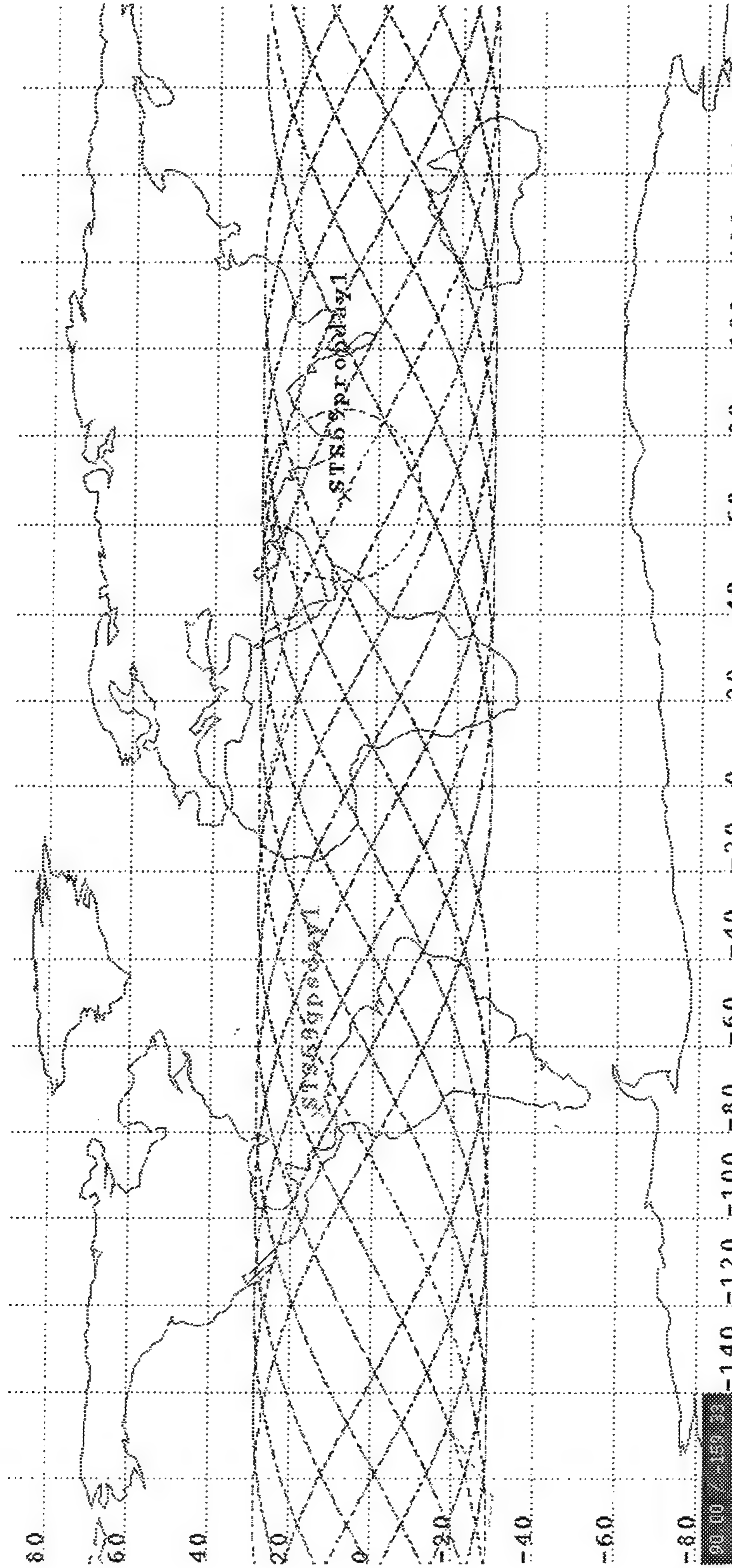

8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
Velocity Vector Magnitude (m/s)
3
3.05
3.1
3.15
3.2
3.25
3.3
3.35
Day 250 Mission Seconds
x 10^4
GPS
Reference

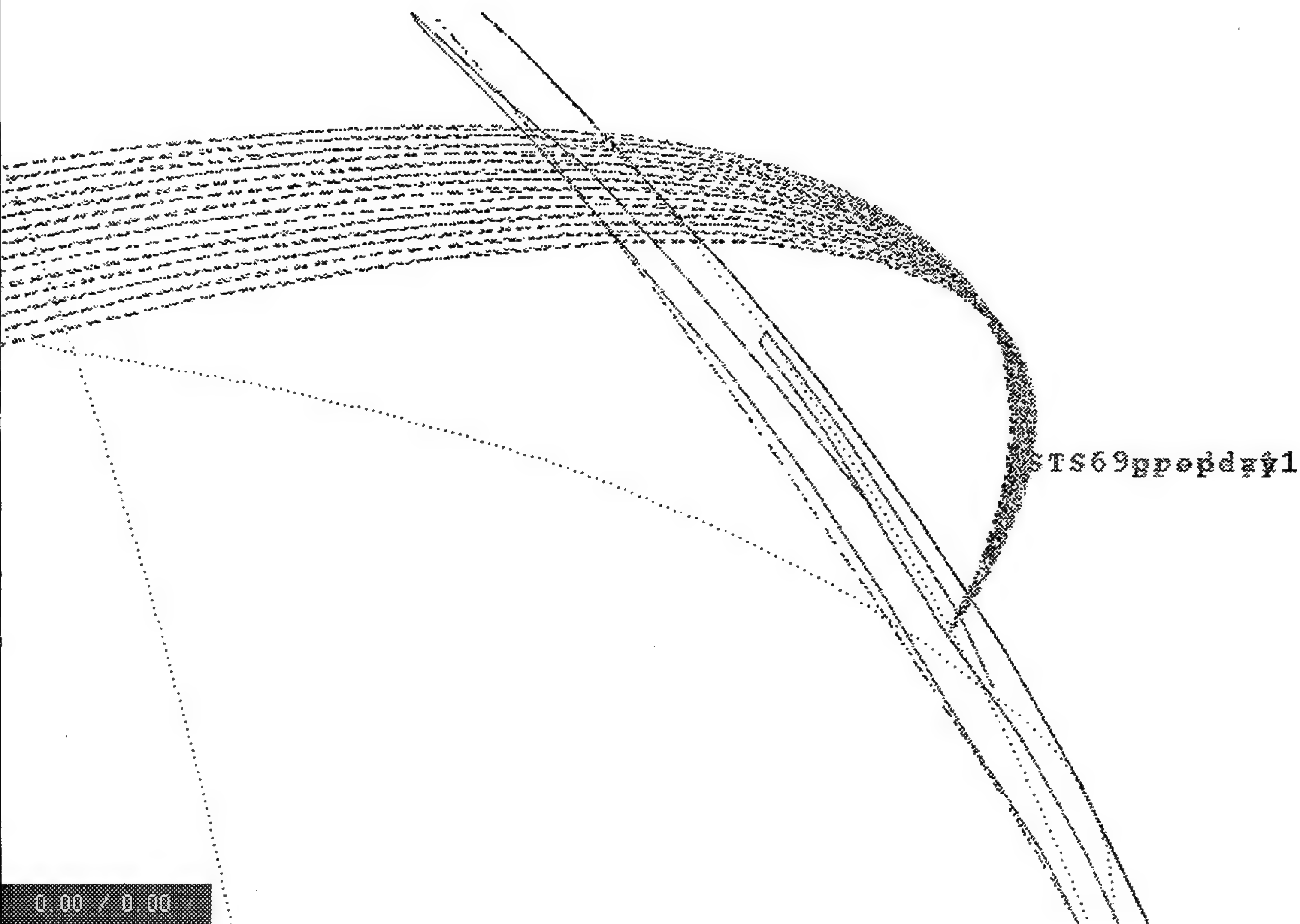
GPS Orbit for Day 250 in J2000 Coordinates

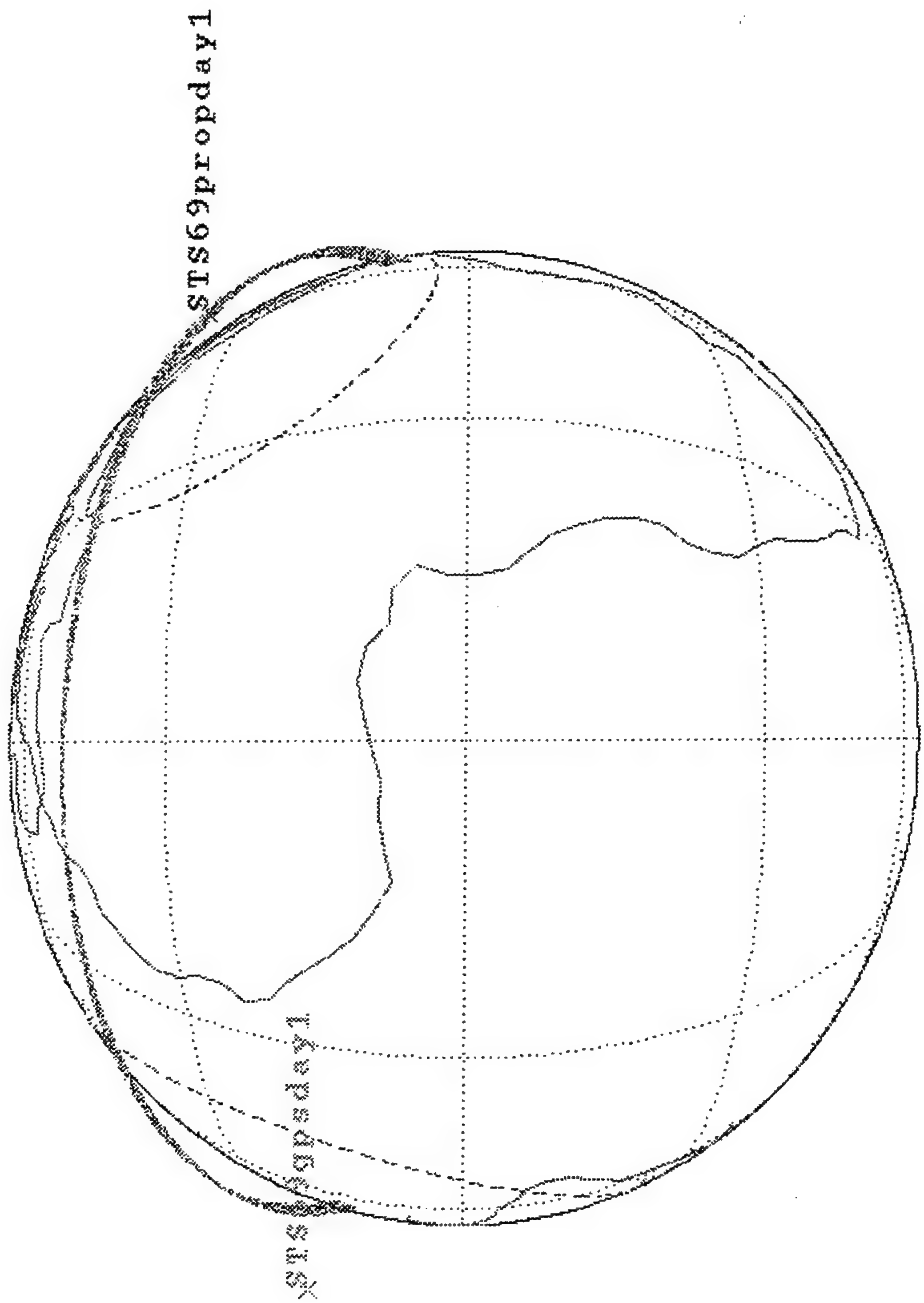


APPENDIX J. DAY 251 STK PLOTS

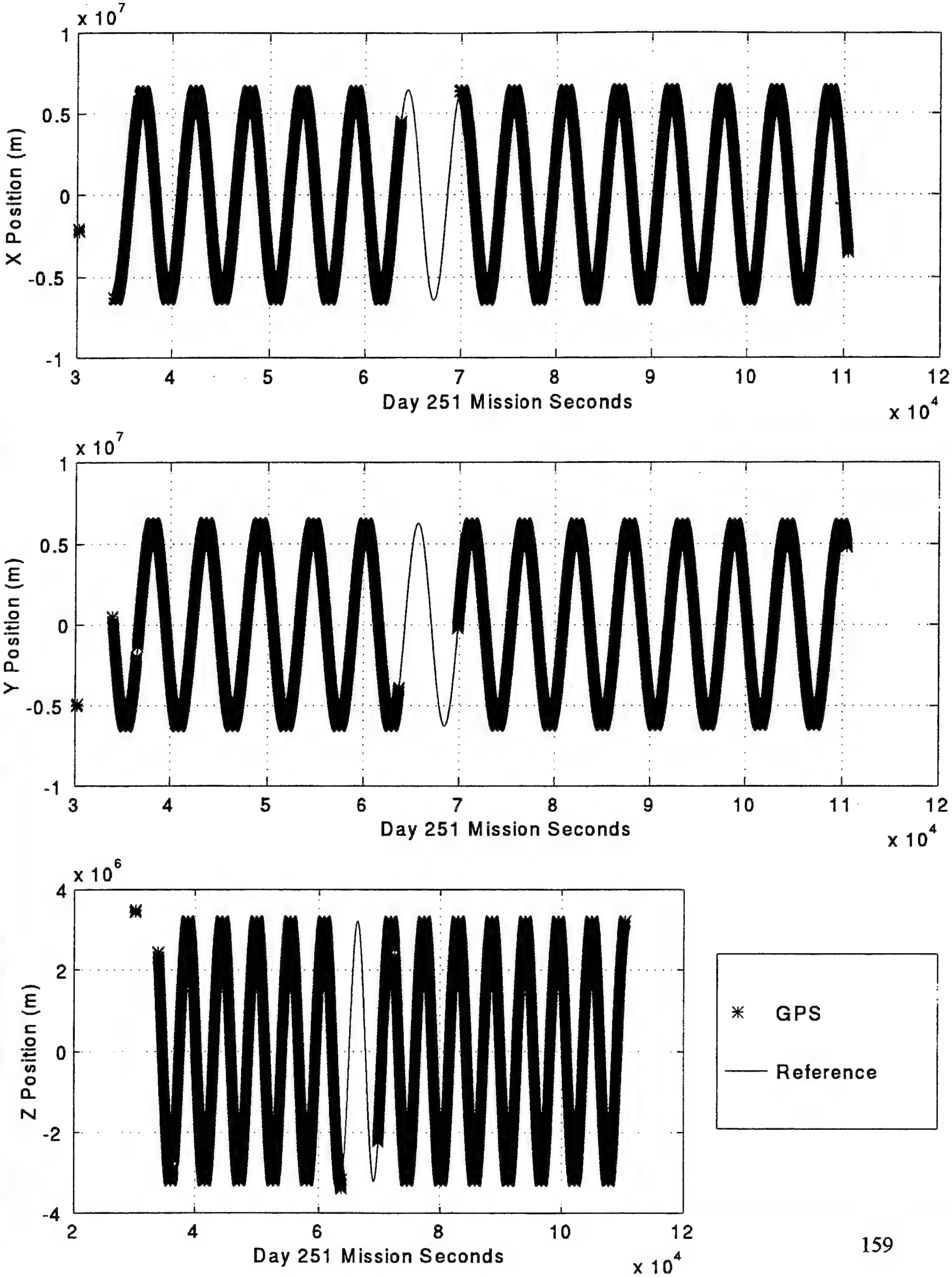

80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

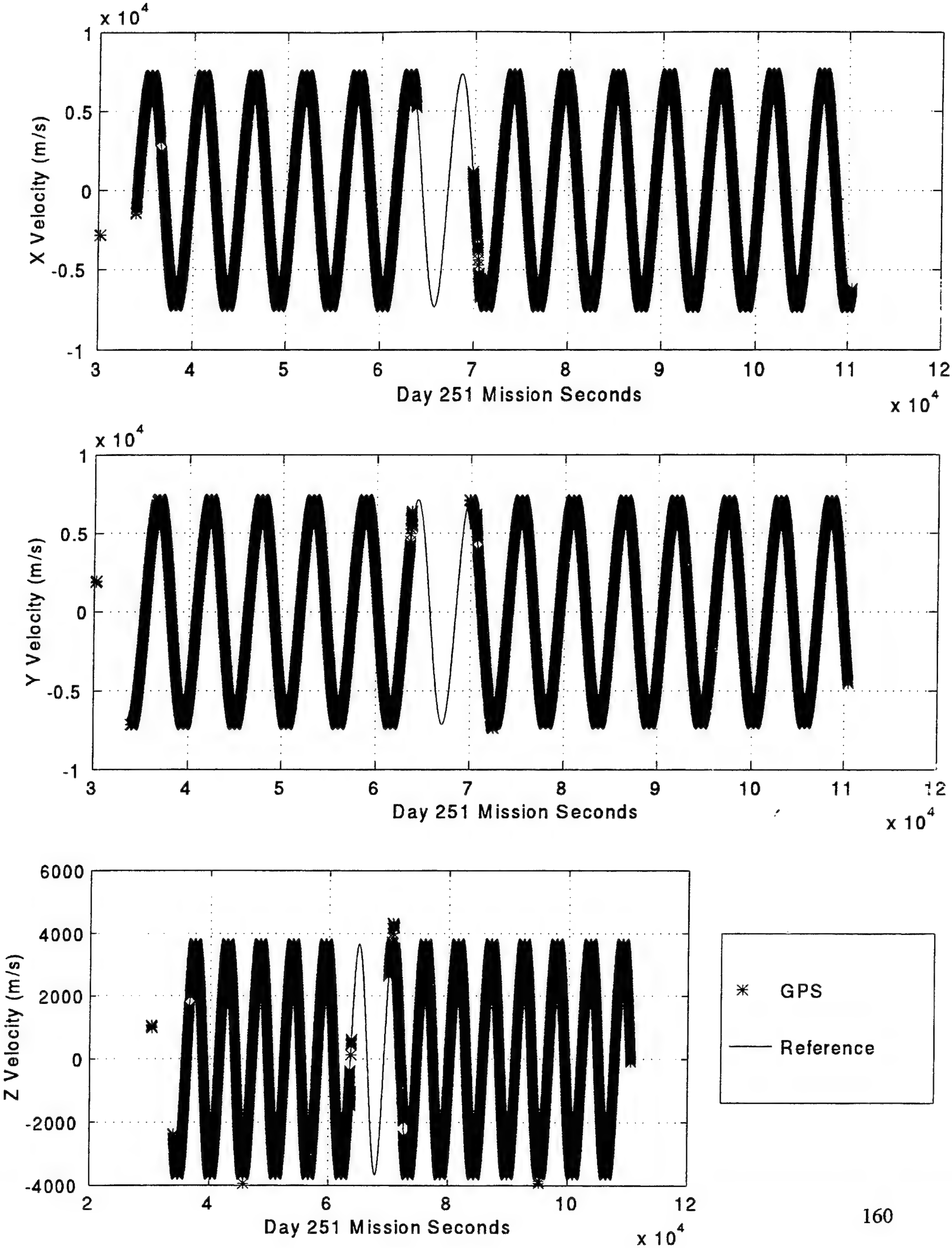

80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

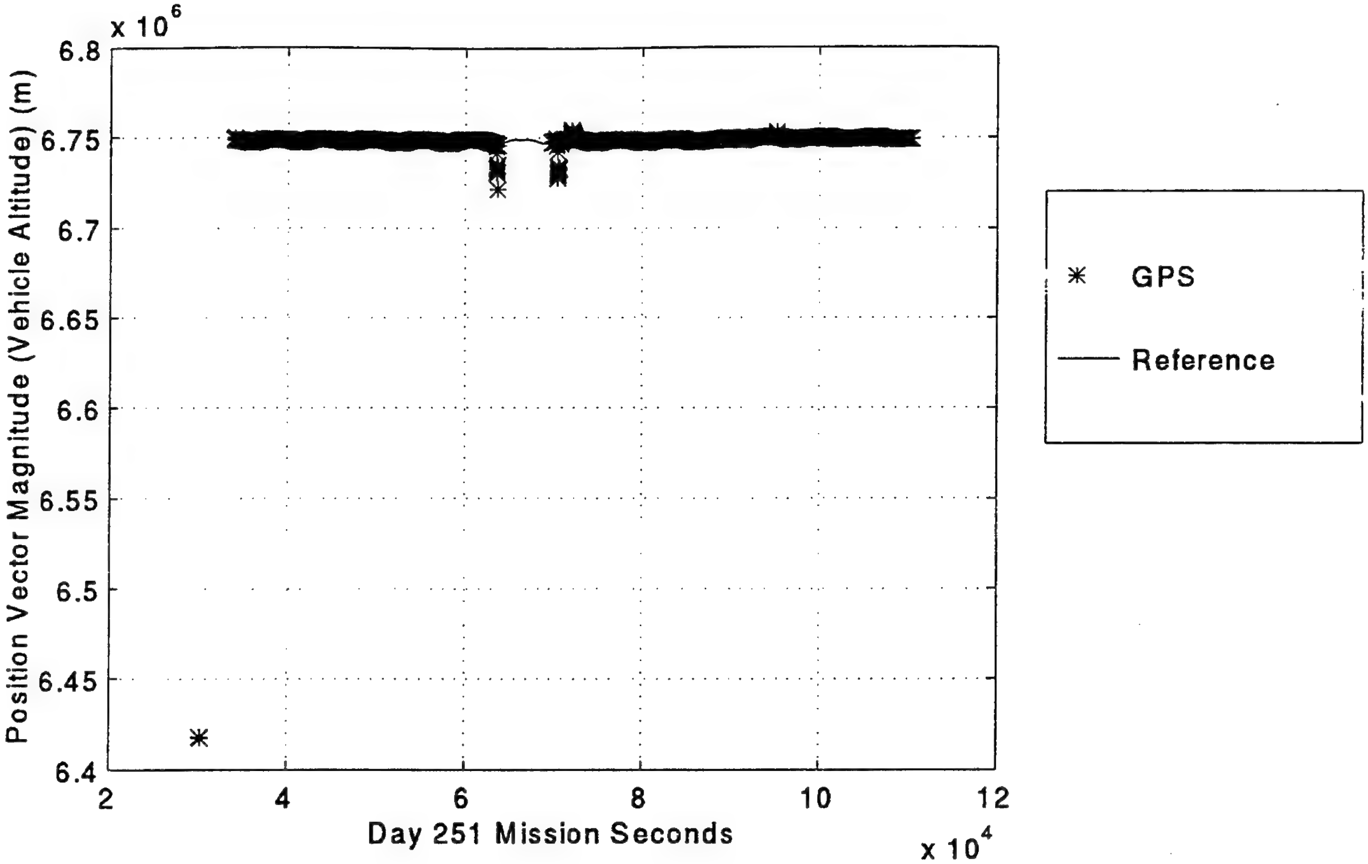

STS69pp
0.00 / 0.00

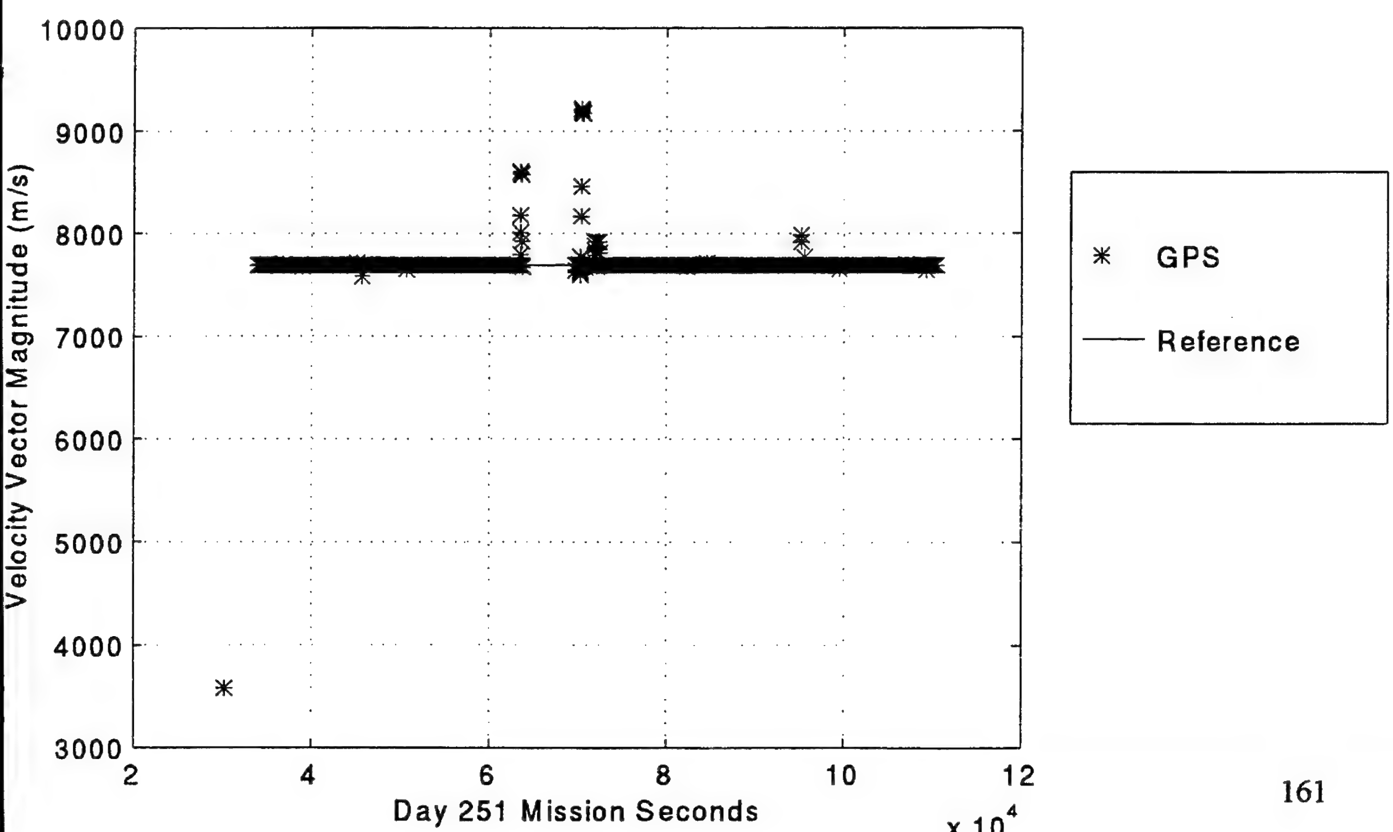

STS69propday1

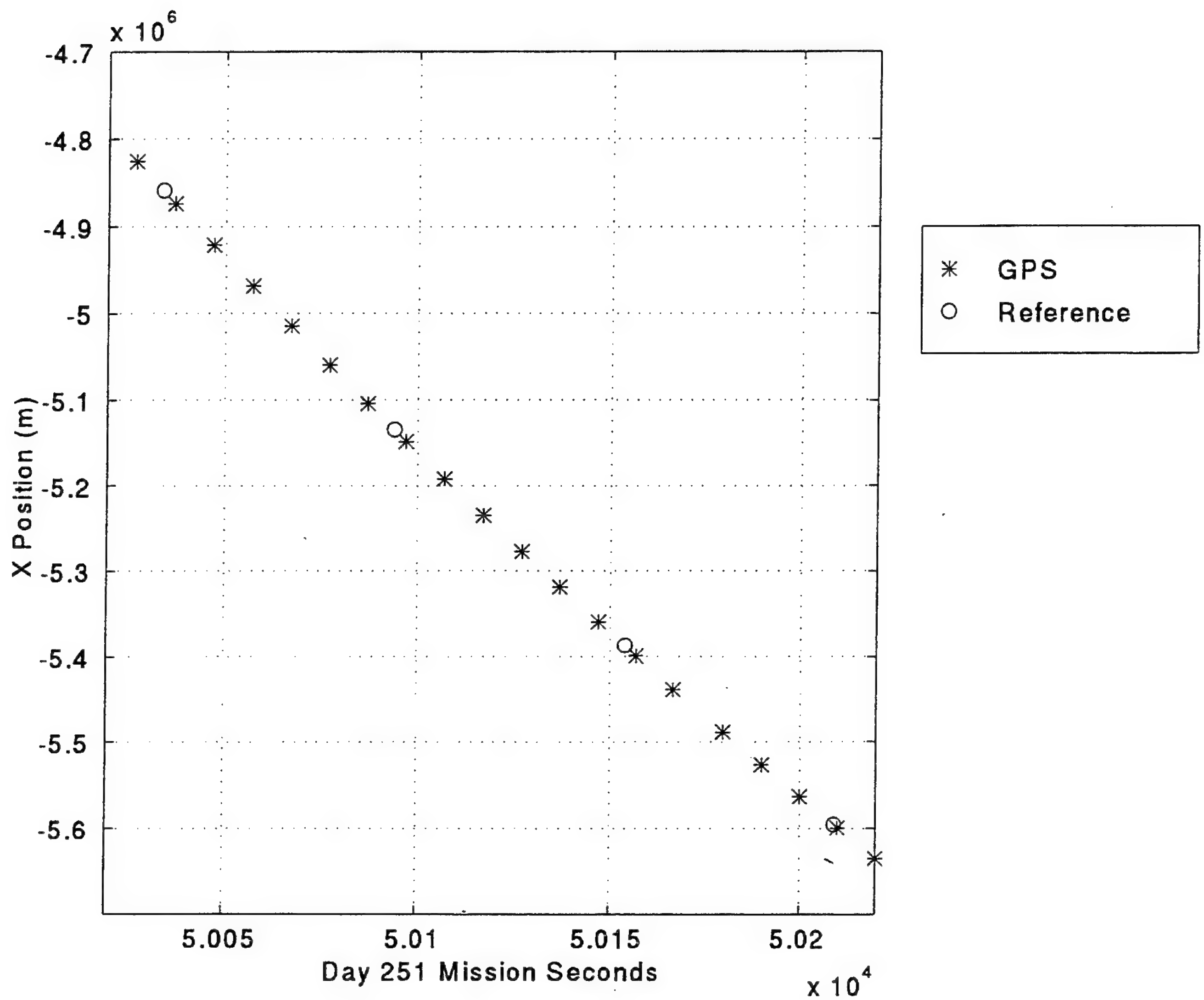
APPENDIX K. DAY 251 MATLAB PLOTS


x 10^7
1
0.5
0
-0.5
-1
X Position (m)
3
4
5
6
7
8
9
10
11
12
Day 251 Mission Seconds
x 10^4
x 10^7
1
0.5
0
-0.5
-1
Y Position (m)
3
4
5
6
7
8
9
10
11
12
Day 251 Mission Seconds
x 10^4
x 10^6
4
2
0
-2
-4
Z Position (m)
2
4
6
8
10
12
Day 251 Mission Seconds
x 10^4
GPS
Reference

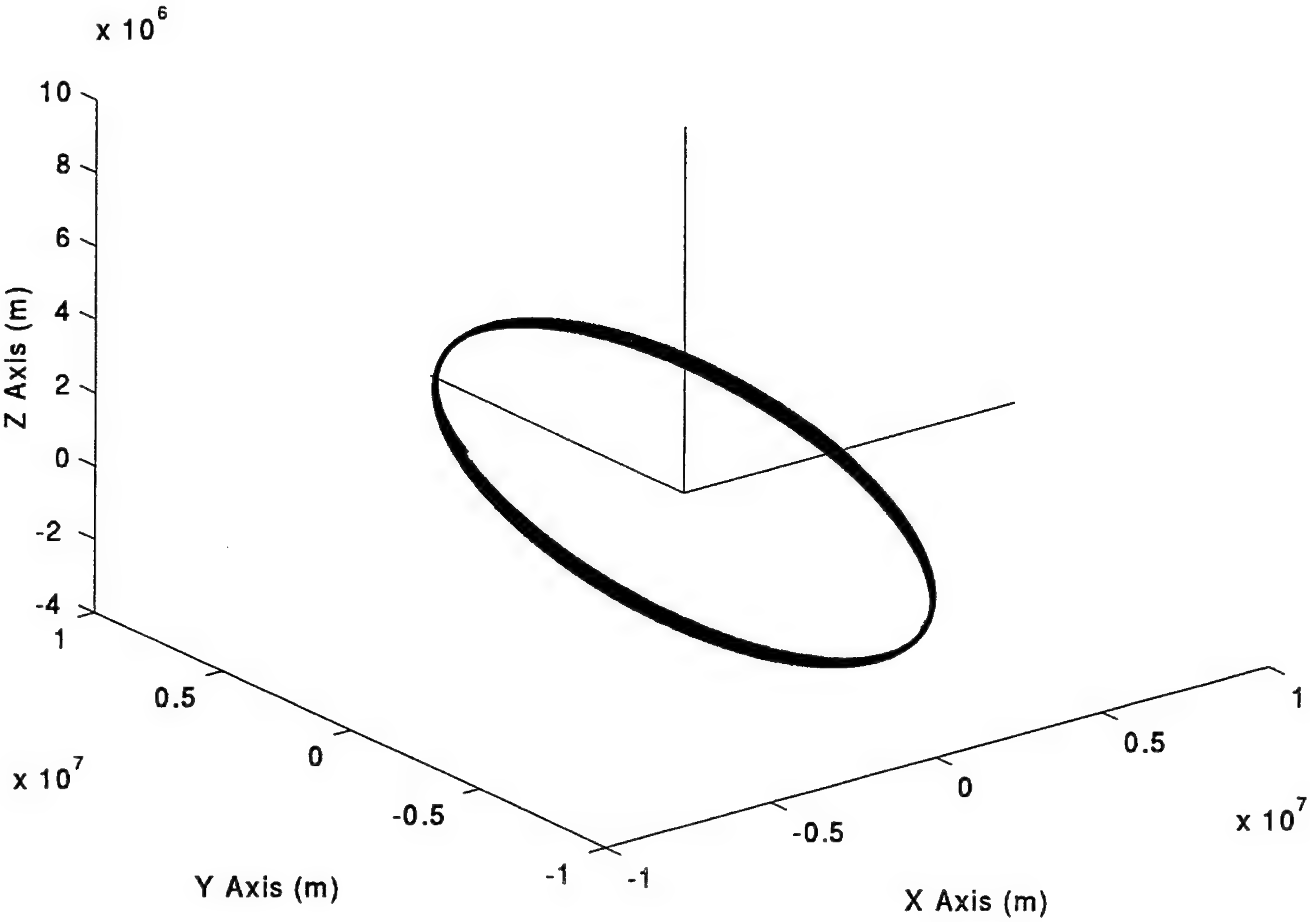

x 10^4
X Velocity (m/s)
Day 251 Mission Seconds
x 10^4
Y Velocity (m/s)
Day 251 Mission Seconds
Z Velocity (m/s)
Day 251 Mission Seconds
GPS
Reference

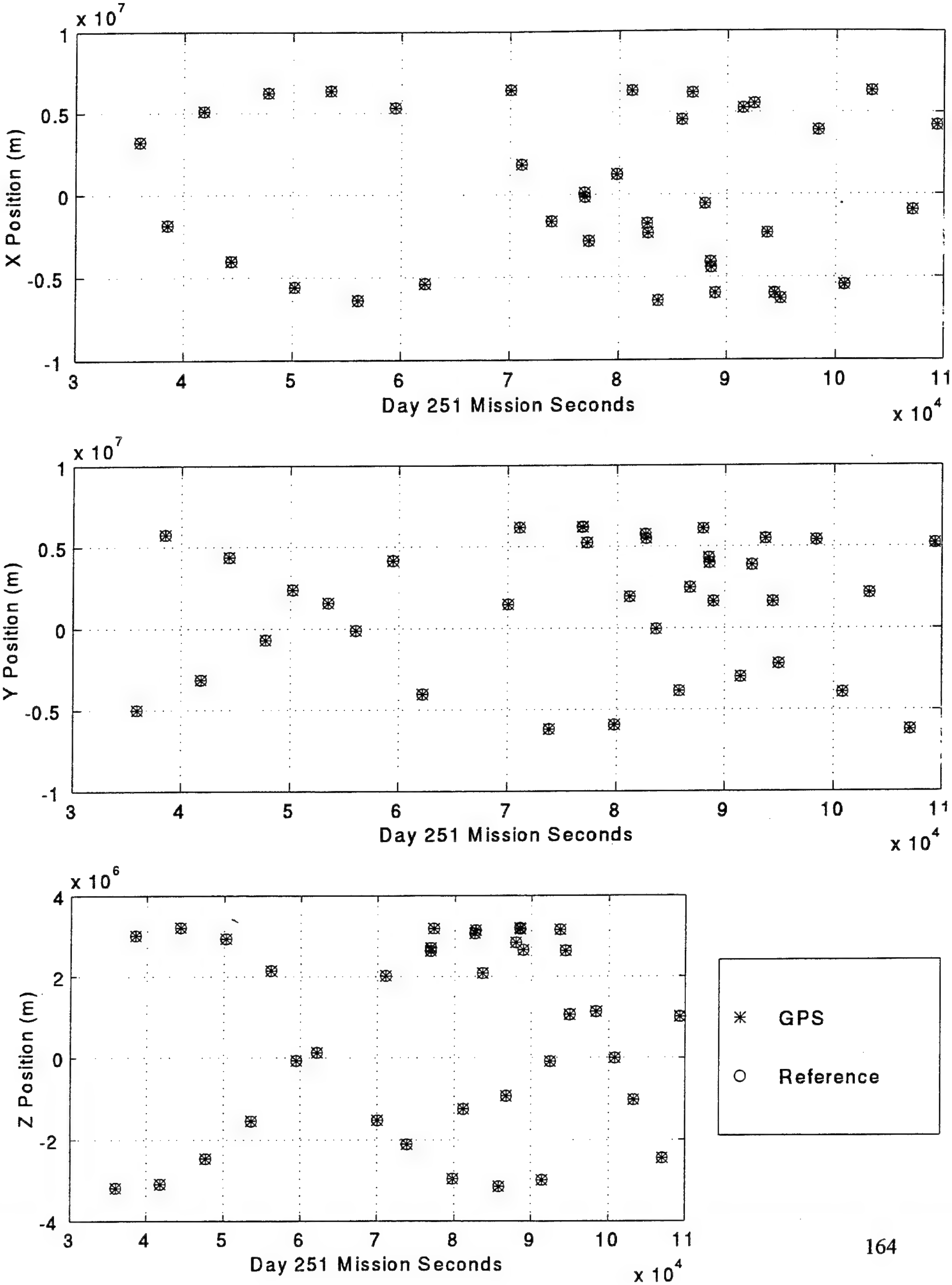

x 10^6
6.8
6.75
6.7
6.65
6.6
6.55
6.5
6.45
6.4
Position Vector Magnitude (Vehicle Altitude) (m)
2
4
6
8
10
12
Day 251 Mission Seconds
x 10^4
GPS
Reference


10000
9000
8000
7000
6000
5000
4000
3000
Velocity Vector Magnitude (m/s)
2
4
6
8
10
12
Day 251 Mission Seconds
x 10^4
GPS
Reference

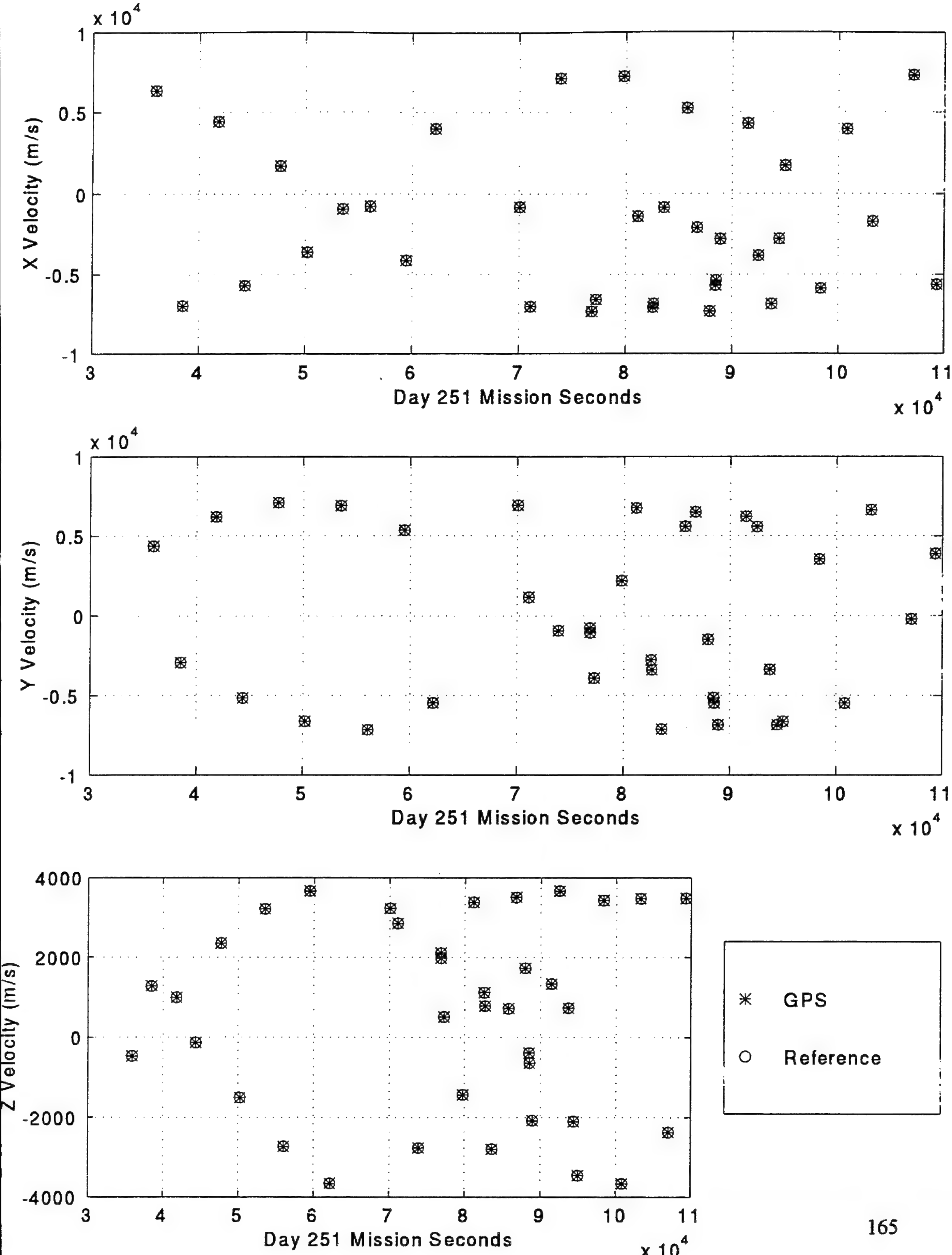

x 10^6
-4.7
-4.8
-4.9
-5
-5.1
-5.2
-5.3
-5.4
-5.5
-5.6
X Position (m)
5.005
5.01
5.015
5.02
Day 251 Mission Seconds
x 10^4
GPS
Reference

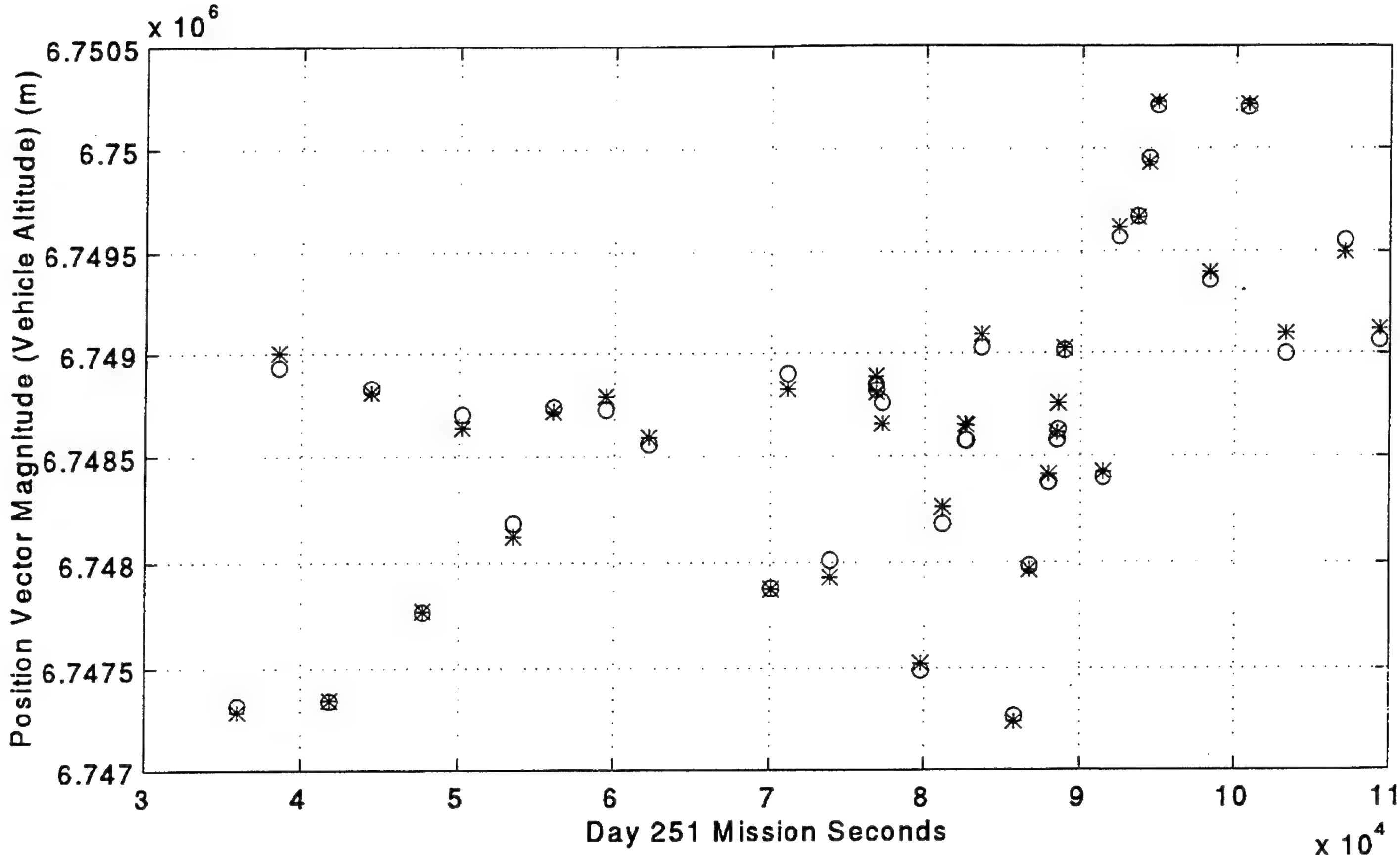
GPS Orbit for Day 251 in J2000 Coordinates

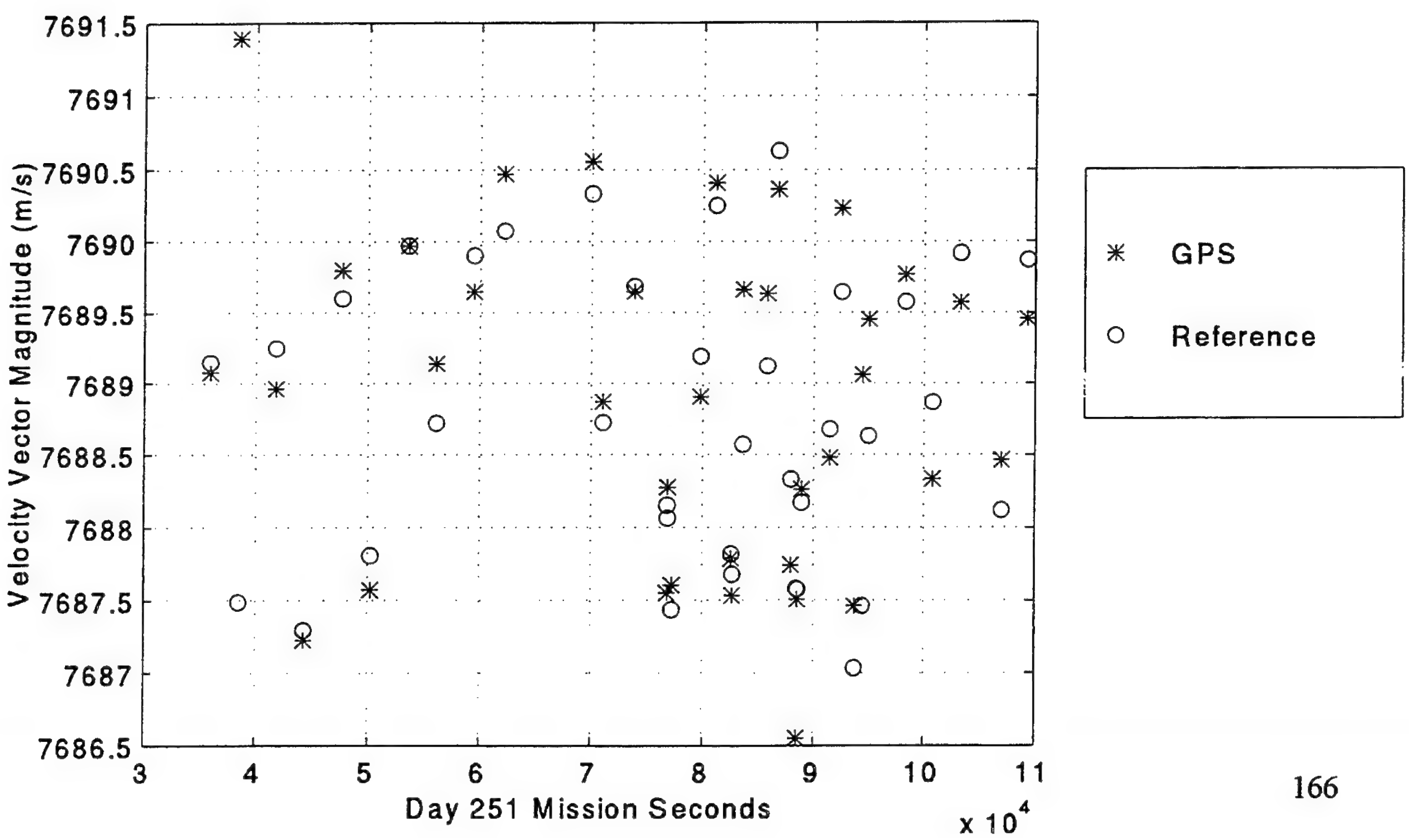


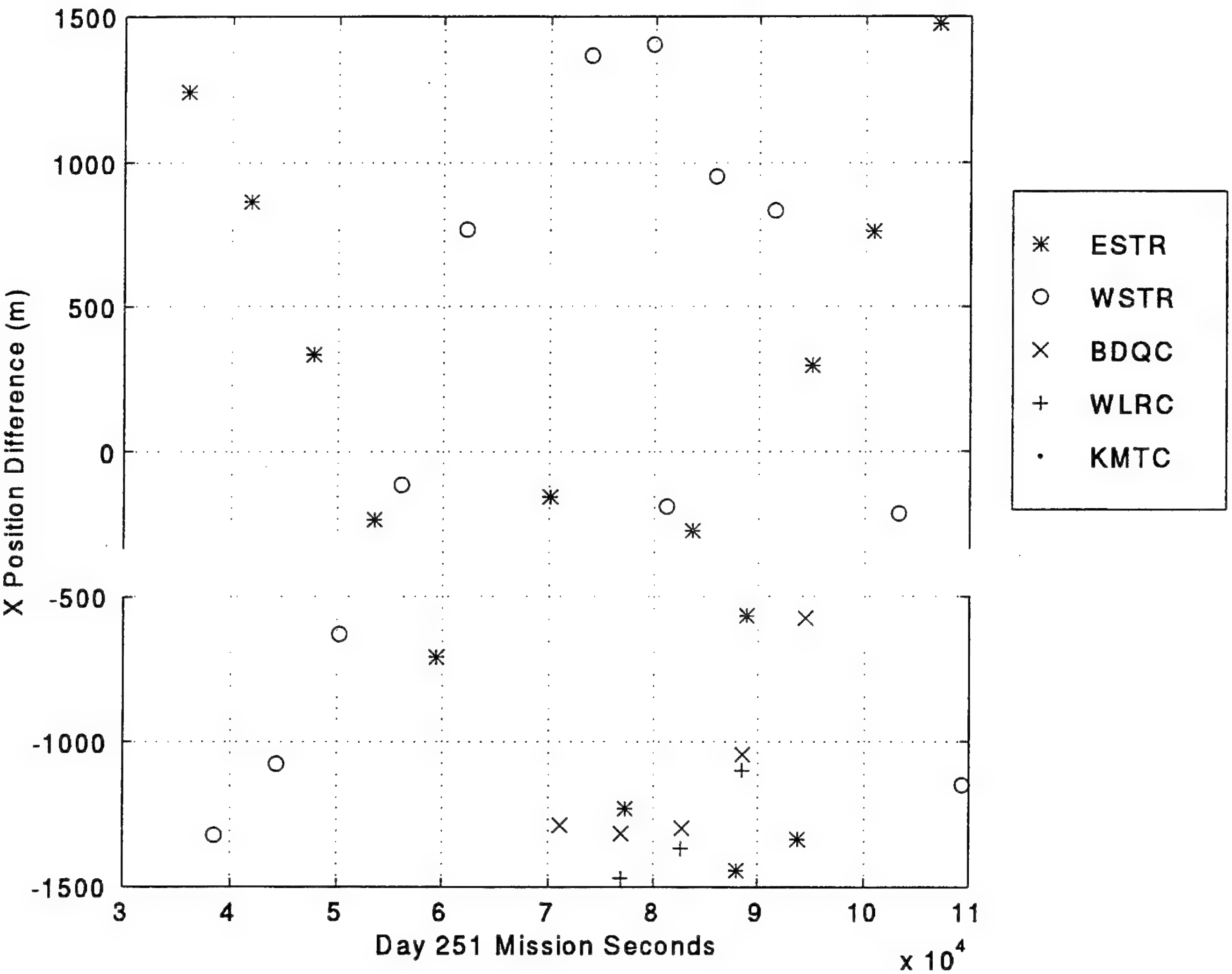


x 10^7
1
0.5
0
-0.5
-1
X Position (m)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
x 10^7
1
0.5
0
-0.5
-1
Y Position (m)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
x 10^6
4
2
0
-2
-4
Z Position (m)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
GPS
Reference

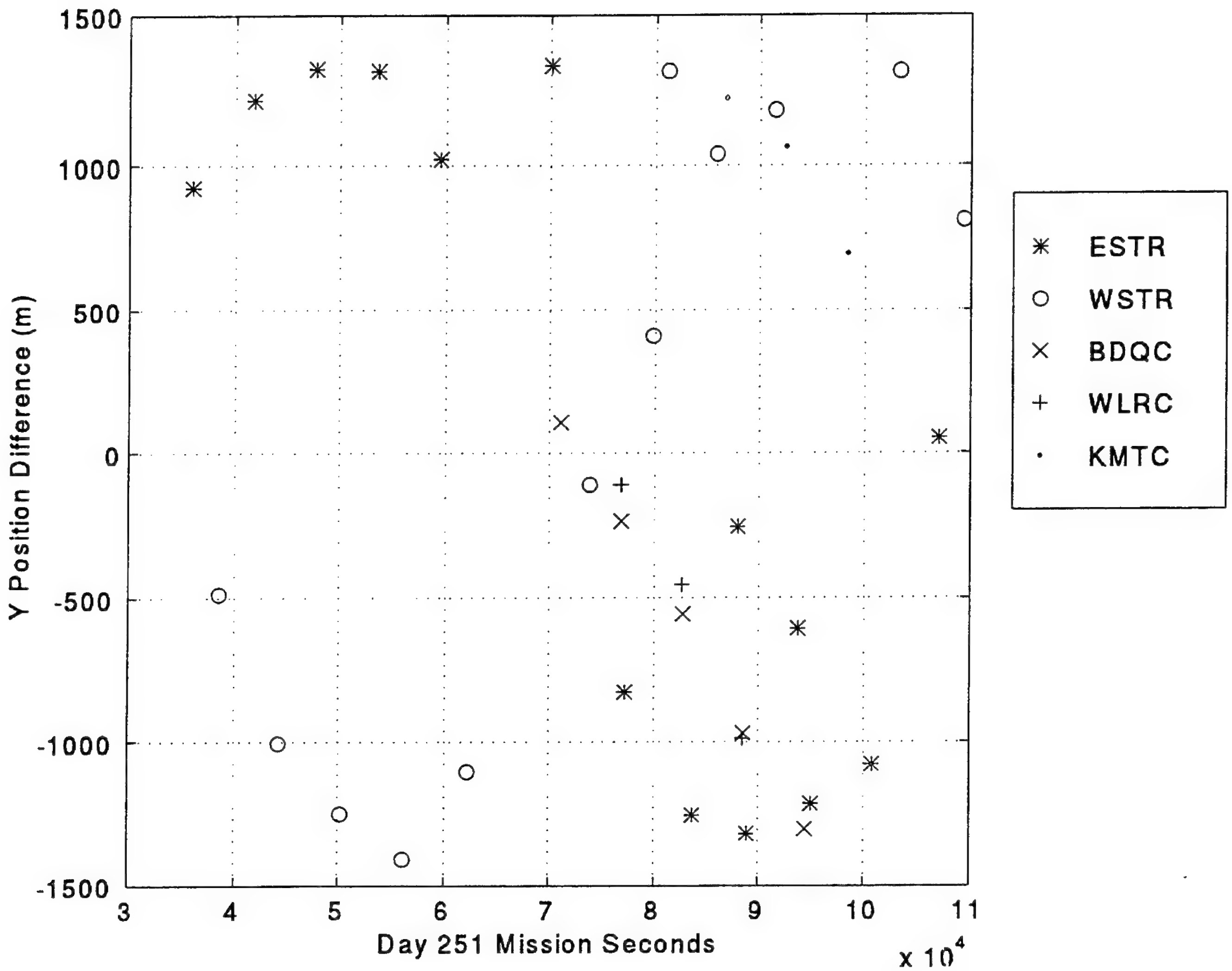

x 10^4
X Velocity (m/s)
Day 251 Mission Seconds
x 10^4
Y Velocity (m/s)
Day 251 Mission Seconds
Z Velocity (m/s)
Day 251 Mission Seconds
GPS
Reference

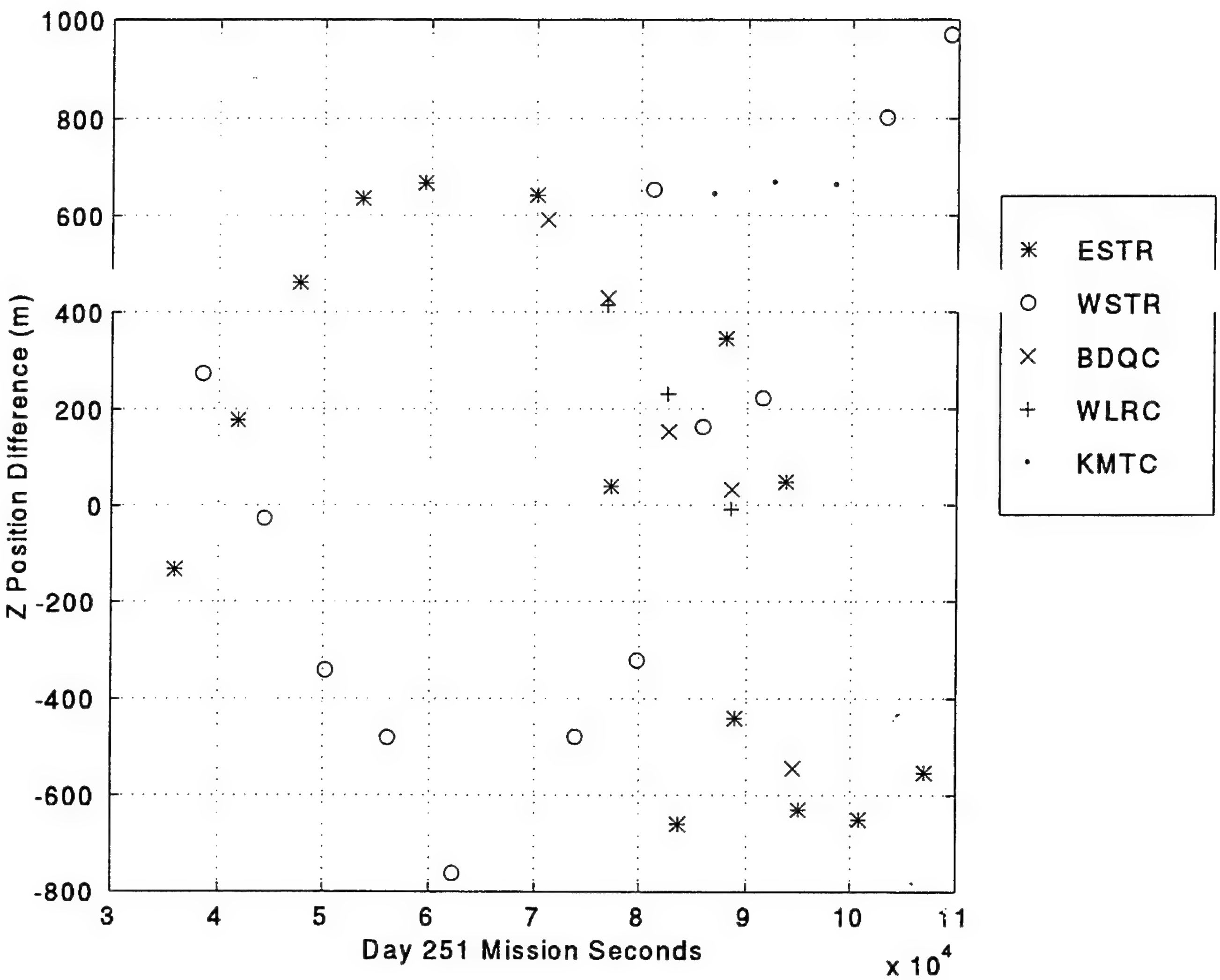

x 10^6
6.7505
6.75
6.7495
6.749
6.7485
6.748
6.7475
6.747
Position Vector Magnitude (Vehicle Altitude) (m)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4

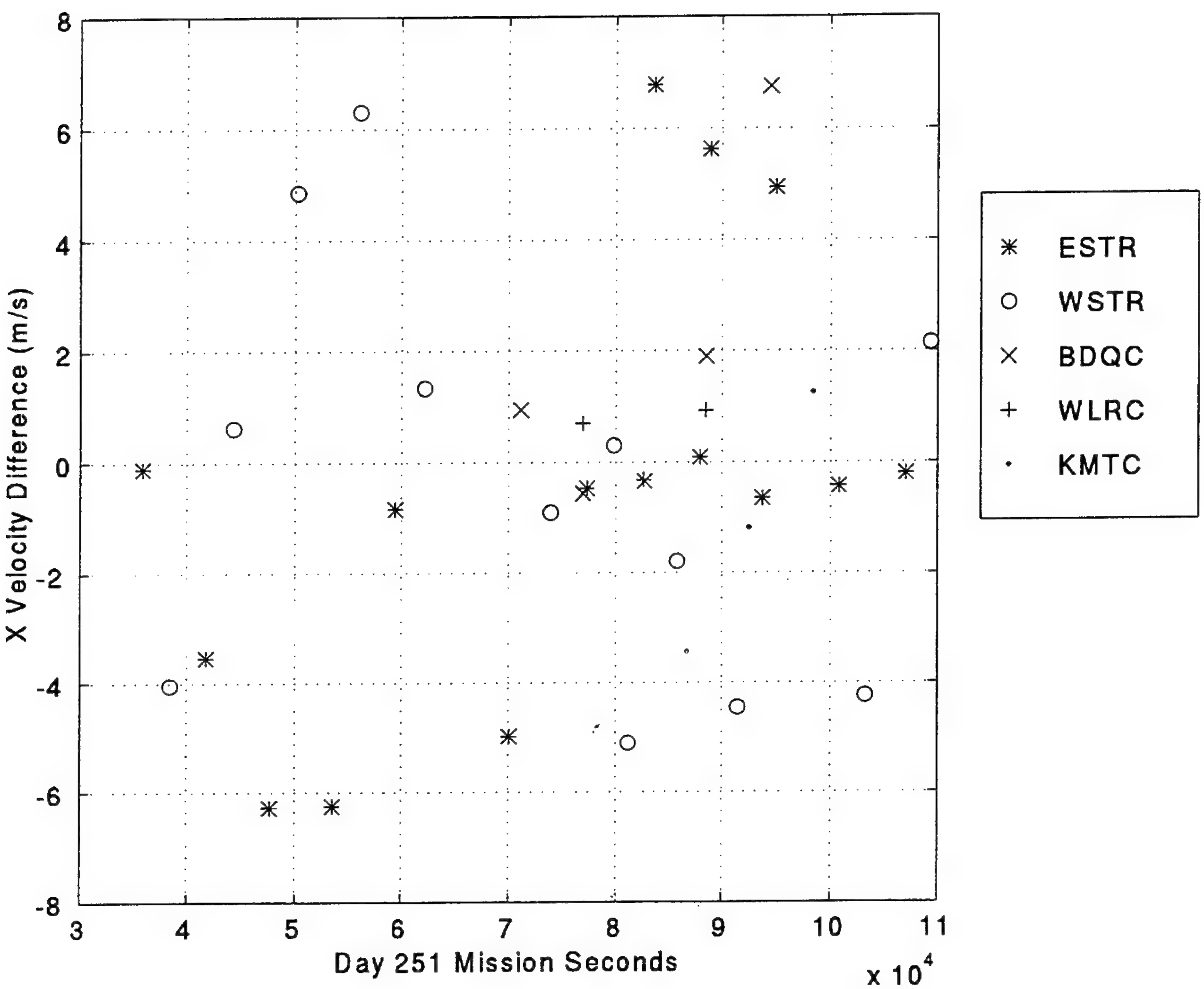

7691.5
7691
7690.5
7690
7689.5
7689
7688.5
7688
7687.5
7687
7686.5
Velocity Vector Magnitude (m/s)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
GPS
Reference



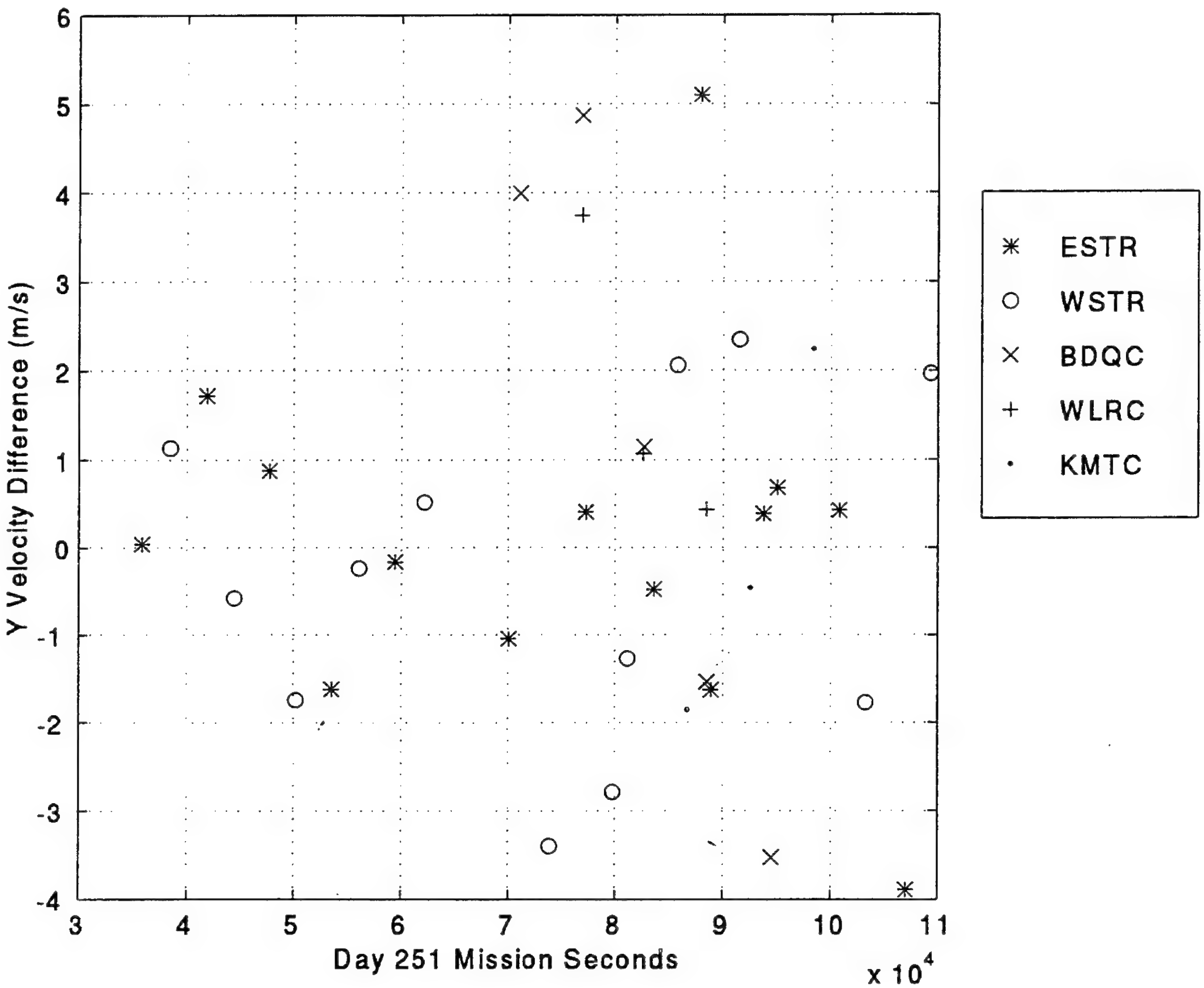
1500
1000
500
0
-500
-1000
-1500
X Position Difference (m)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

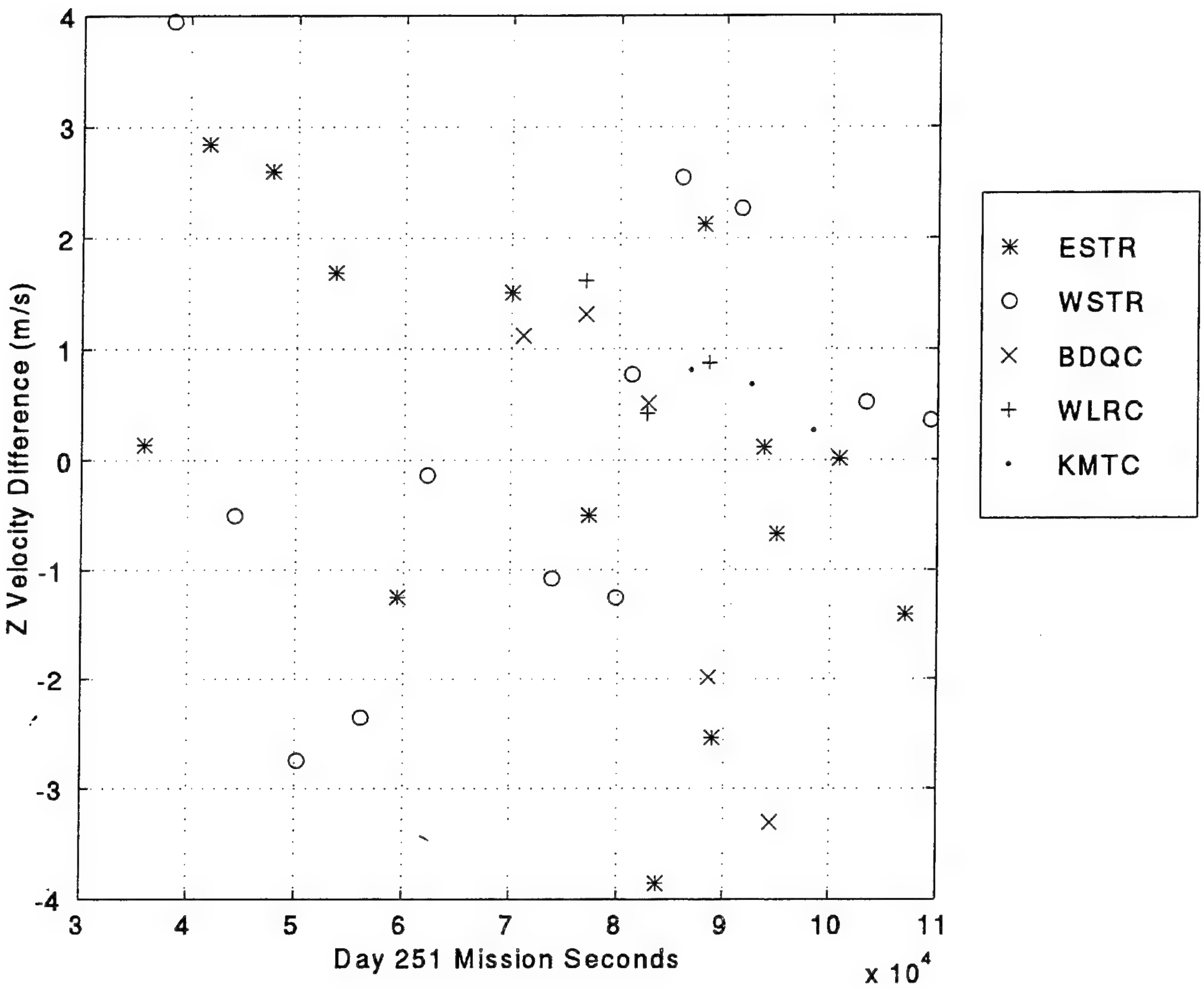

1500
1000
500
0
-500
-1000
-1500
Y Position Difference (m)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

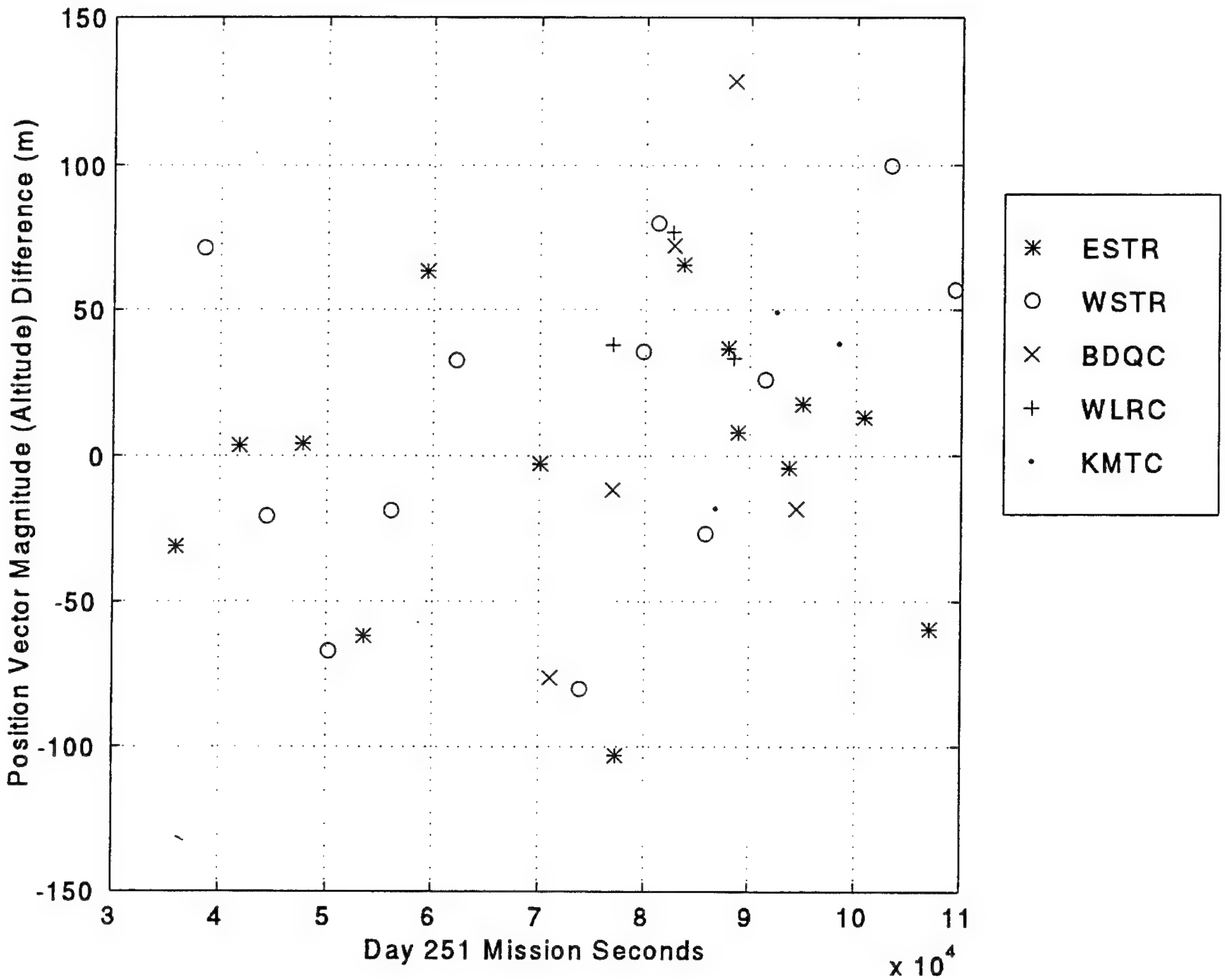

1000
800
600
400
200
0
-200
-400
-600
-800
Z Position Difference (m)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

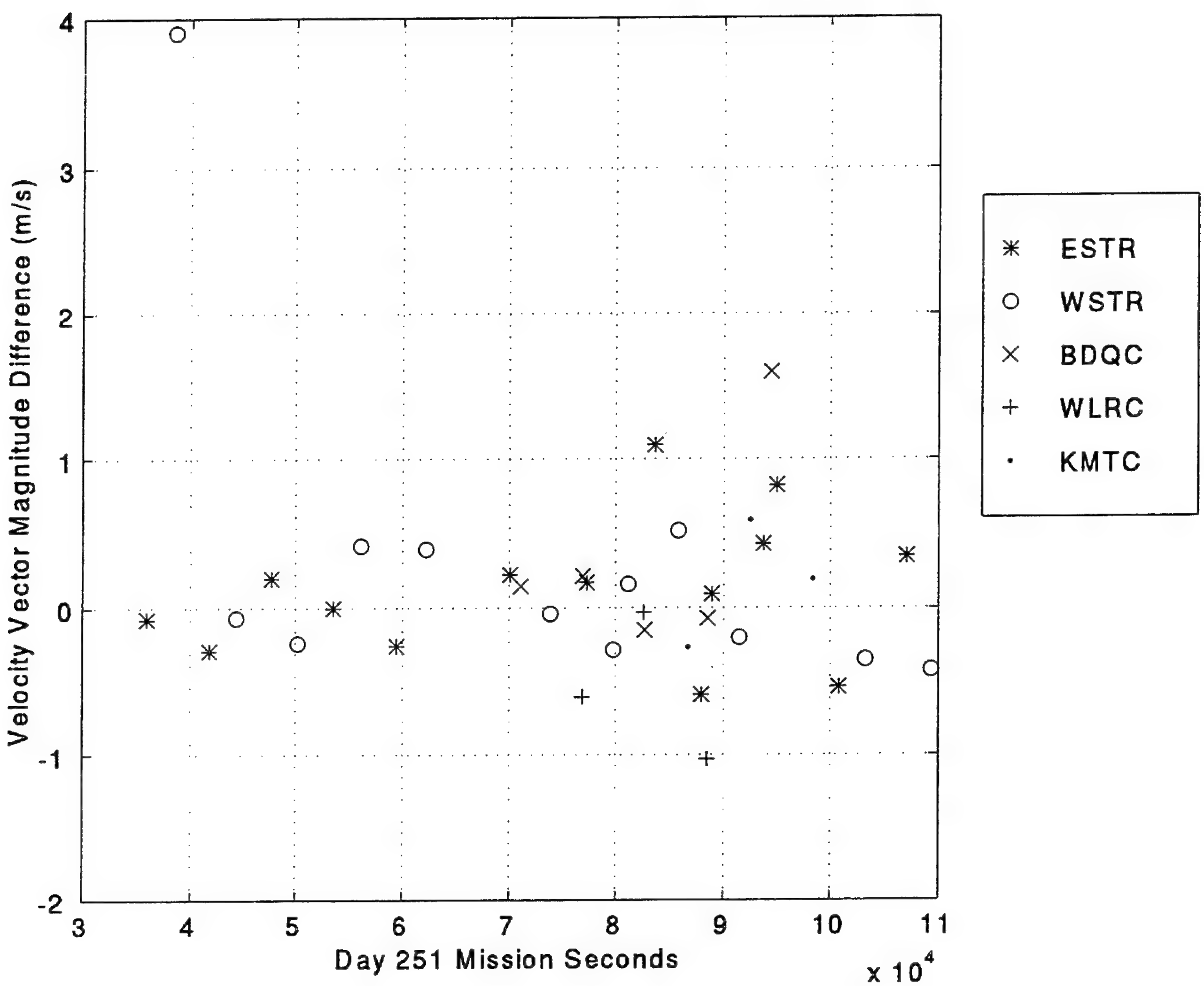


8
6
4
2
0
-2
-4
-6
-8
X Velocity Difference (m/s)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

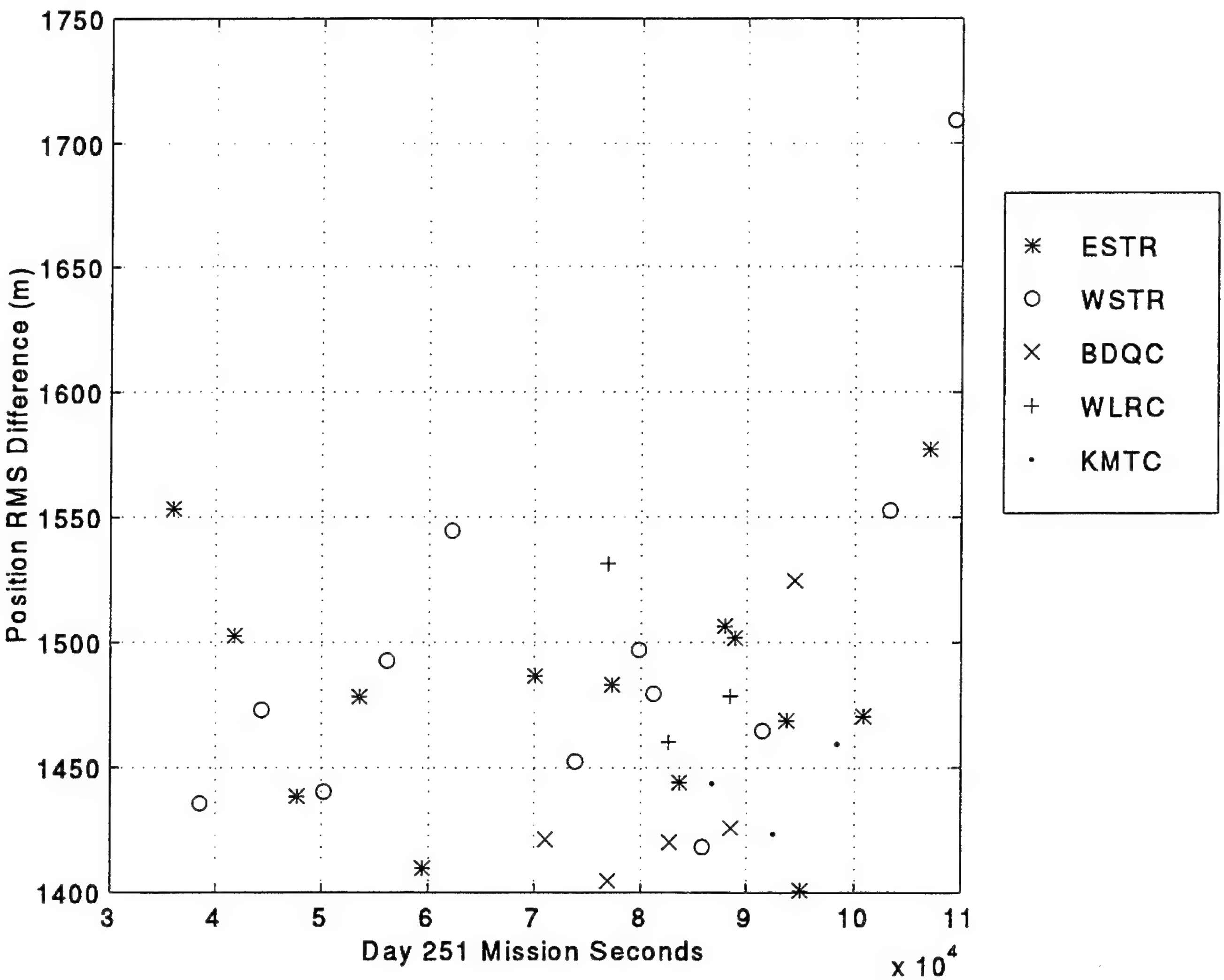

Y Velocity Difference (m/s)
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

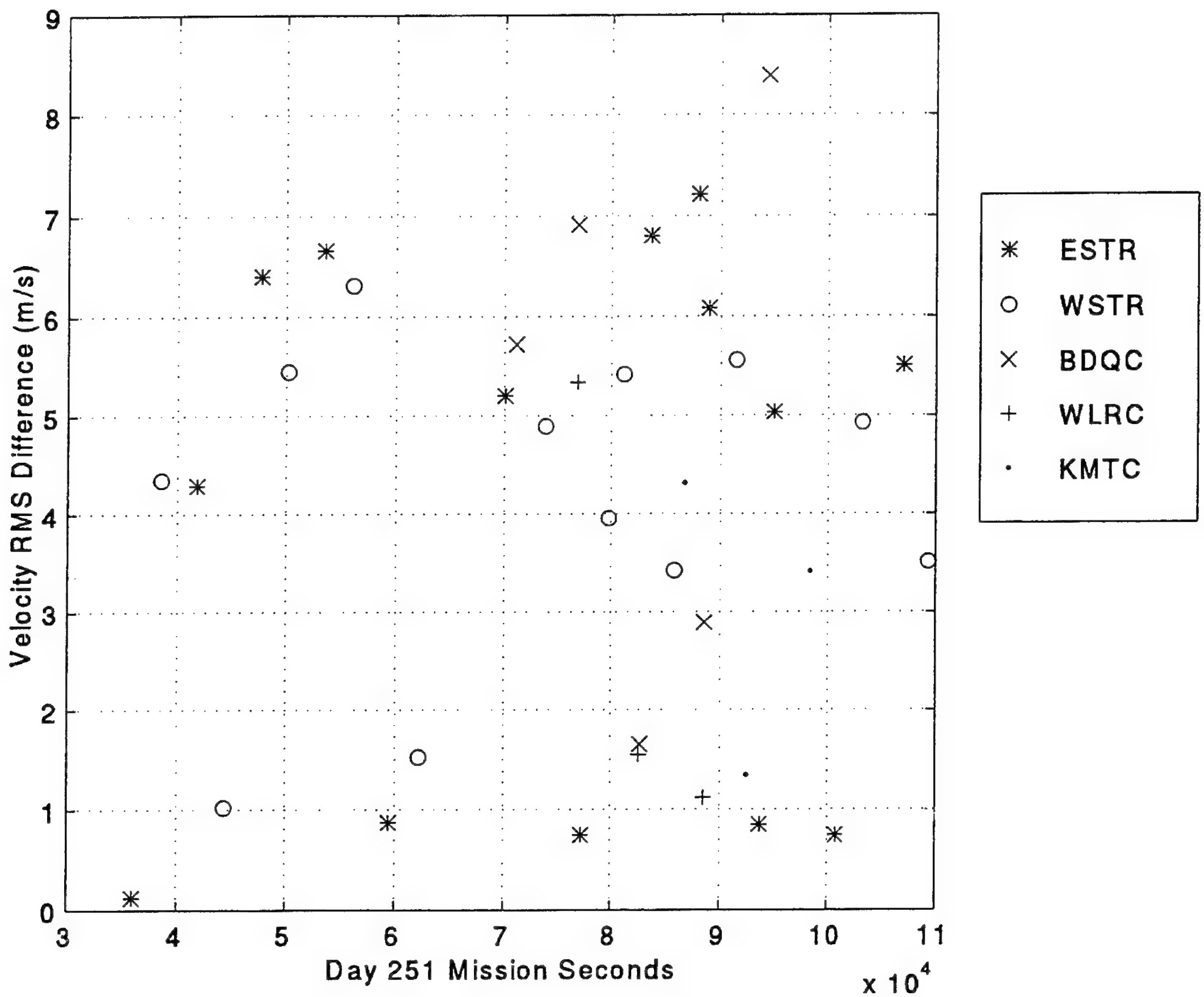

Z Velocity Difference (m/s)
Day 251 Mission Seconds
x 10^4
4
3
2
1
0
-1
-2
-3
-4
3
4
5
6
7
8
9
10
11
ESTR
WSTR
BDQC
WLRC
KMTC


150
100
50
0
-50
-100
-150
3
4
5
6
7
8
9
10
11
x 10^4
Day 251 Mission Seconds
Position Vector Magnitude (Altitude) Difference (m)
ESTR
WSTR
BDQC
WLRC
KMTC



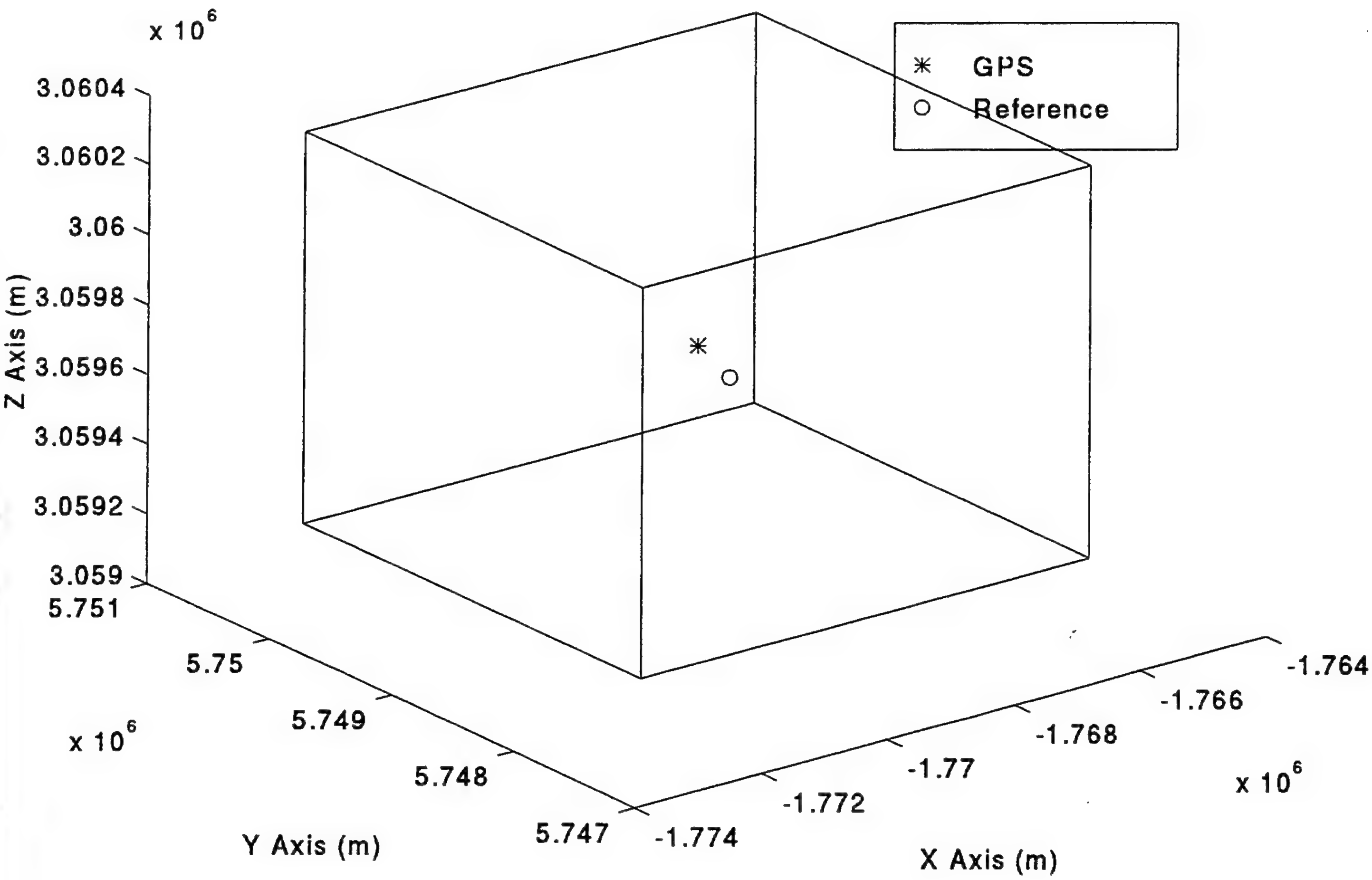
Velocity Vector Magnitude Difference (m/s)
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

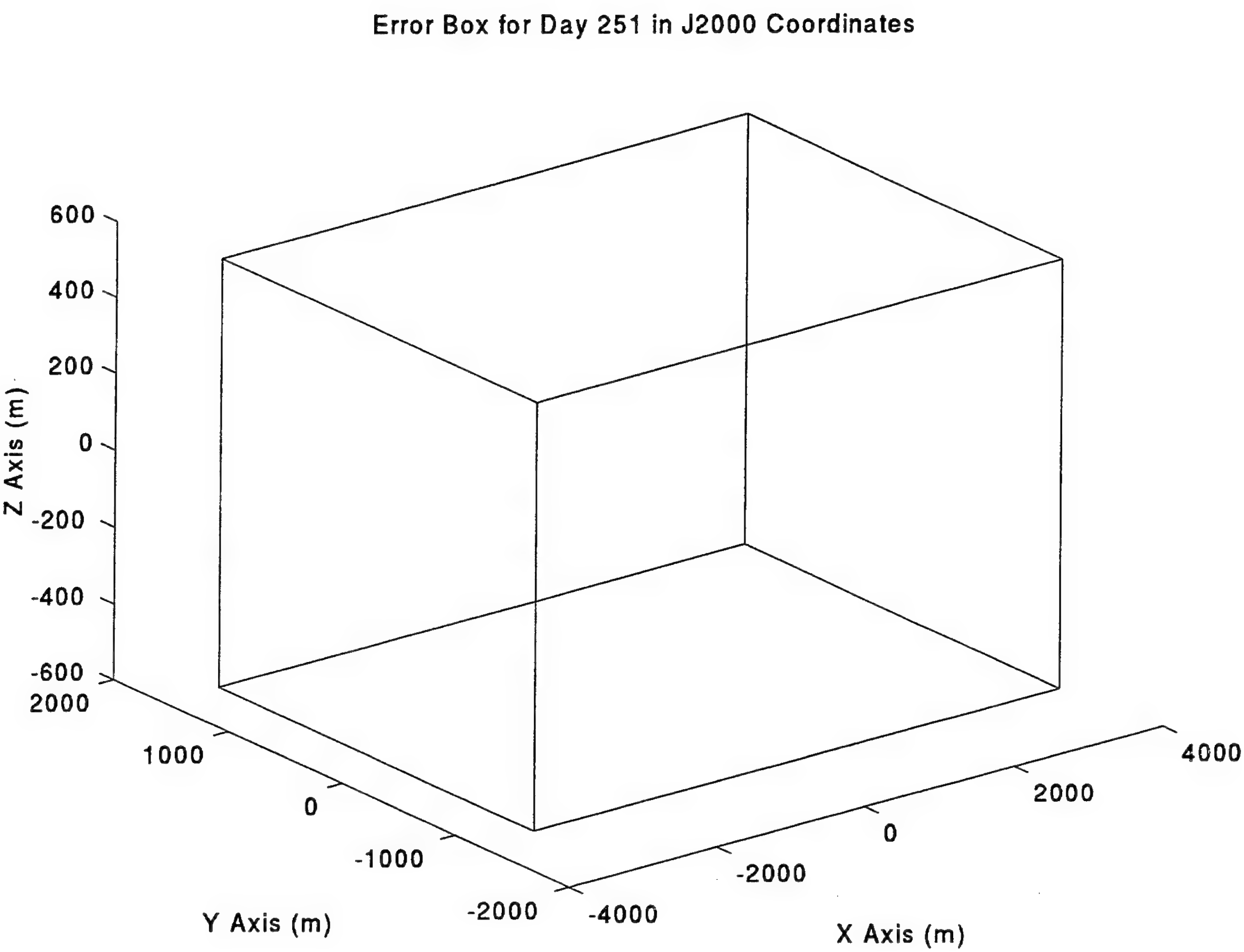

1750
1700
1650
1600
1550
1500
1450
1400
Position RMS Difference (m)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

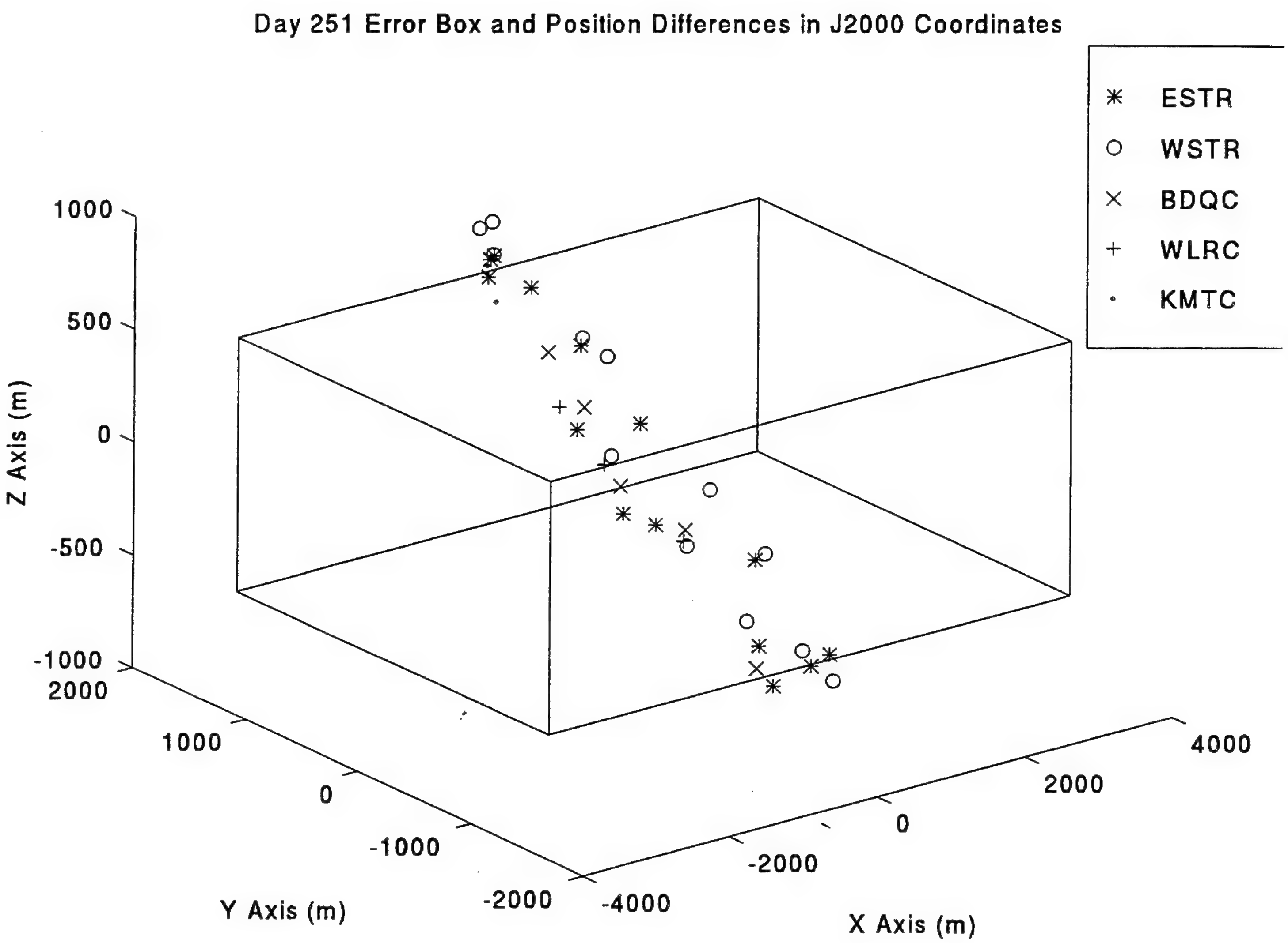


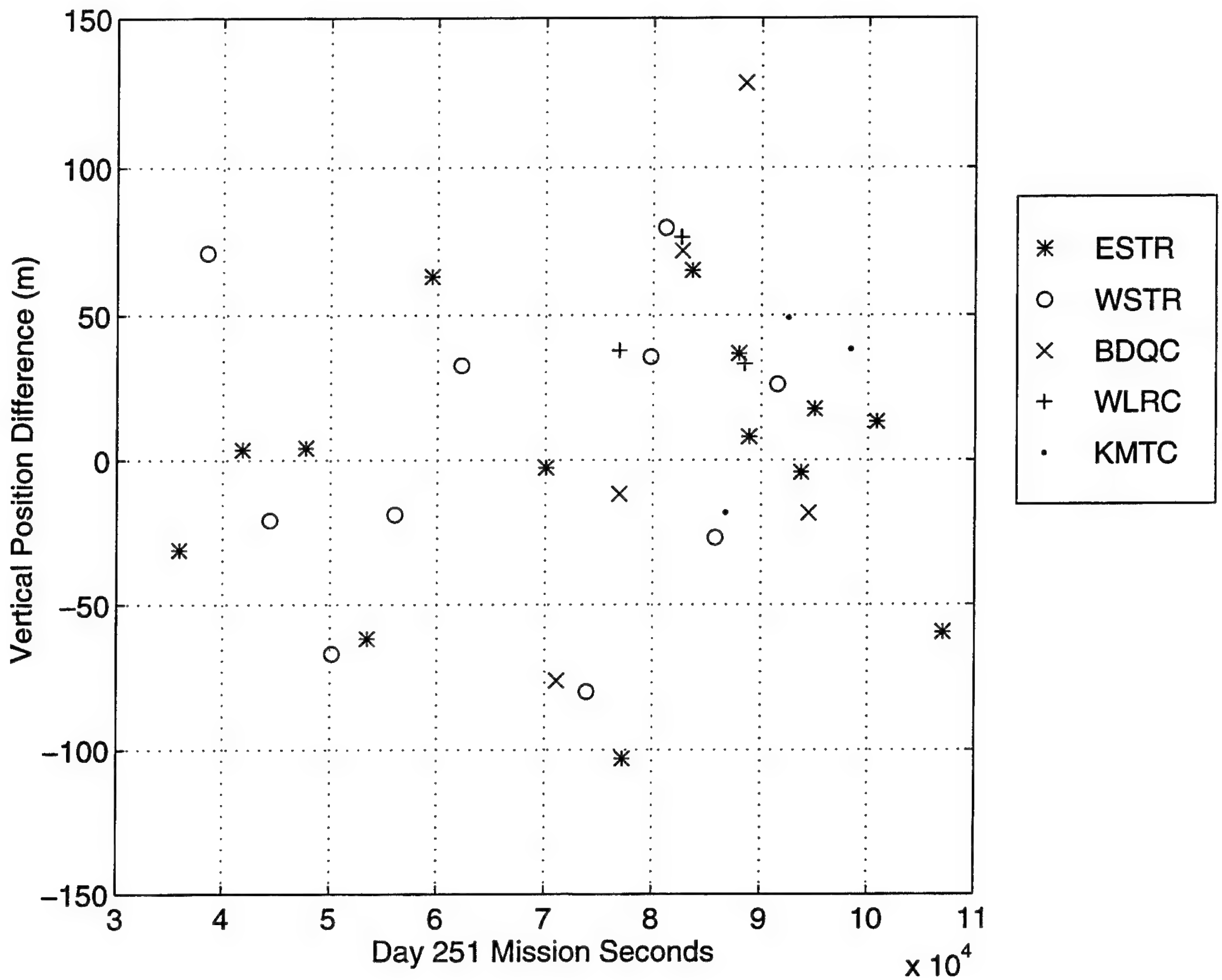
Velocity RMS Difference (m/s)
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

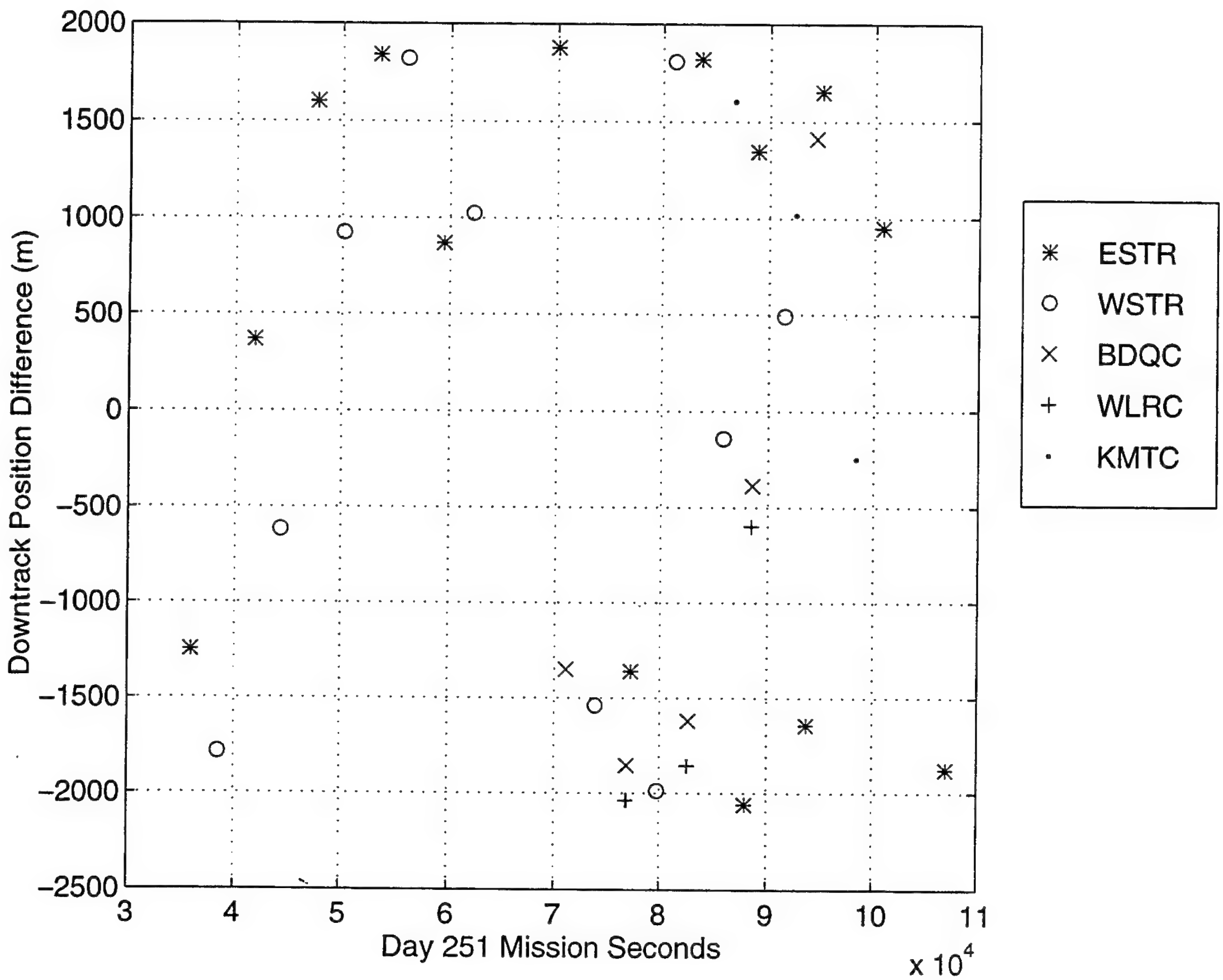
Day 251 GPS and Reference Positions in J2000 Coordinates



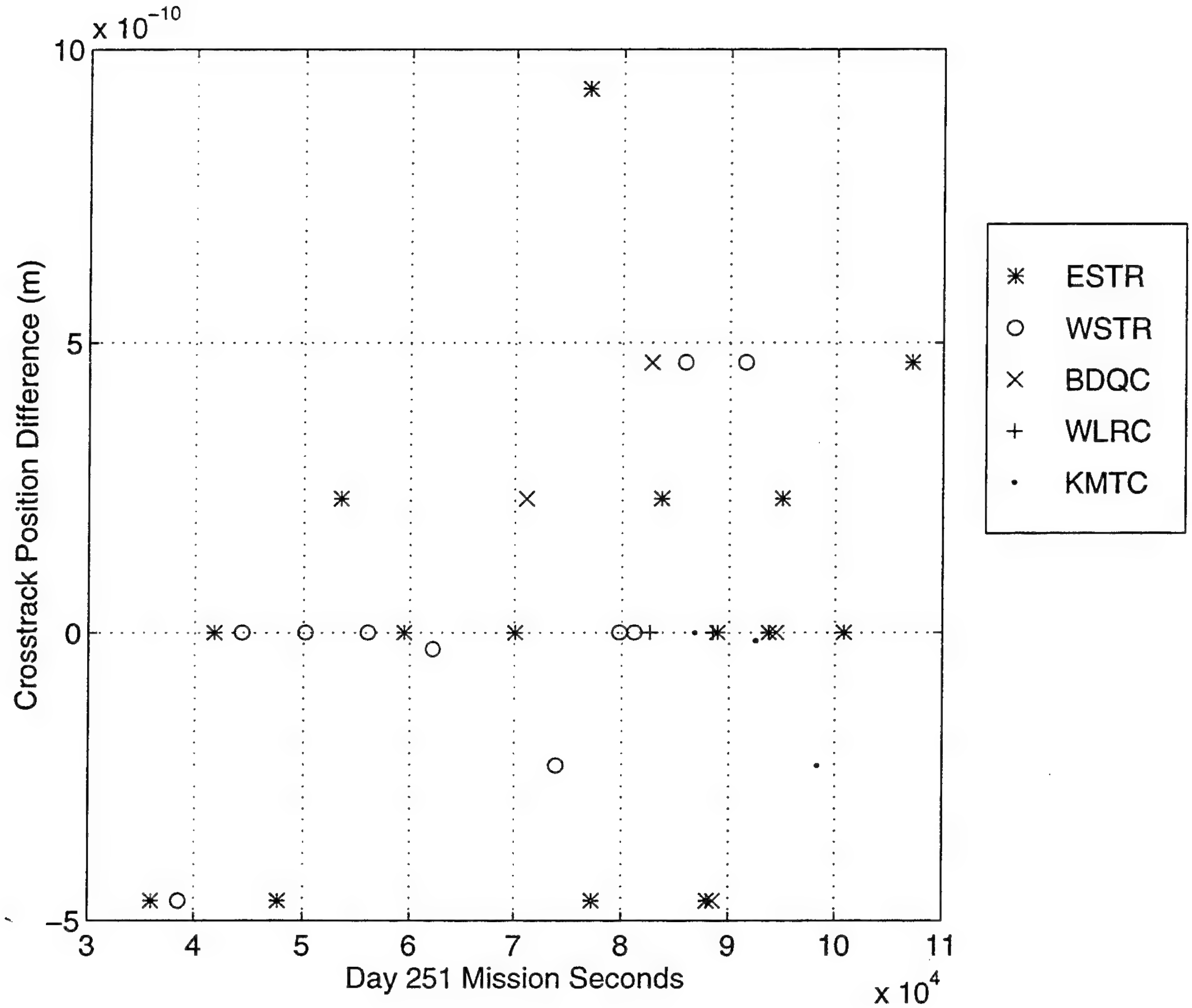

Error Box for Day 251 in J2000 Coordinates
600
400
200
0
-200
-400
-600
Z Axis (m)
2000
1000
0
-1000
-2000
Y Axis (m)
-4000
-2000
0
2000
4000
X Axis (m)

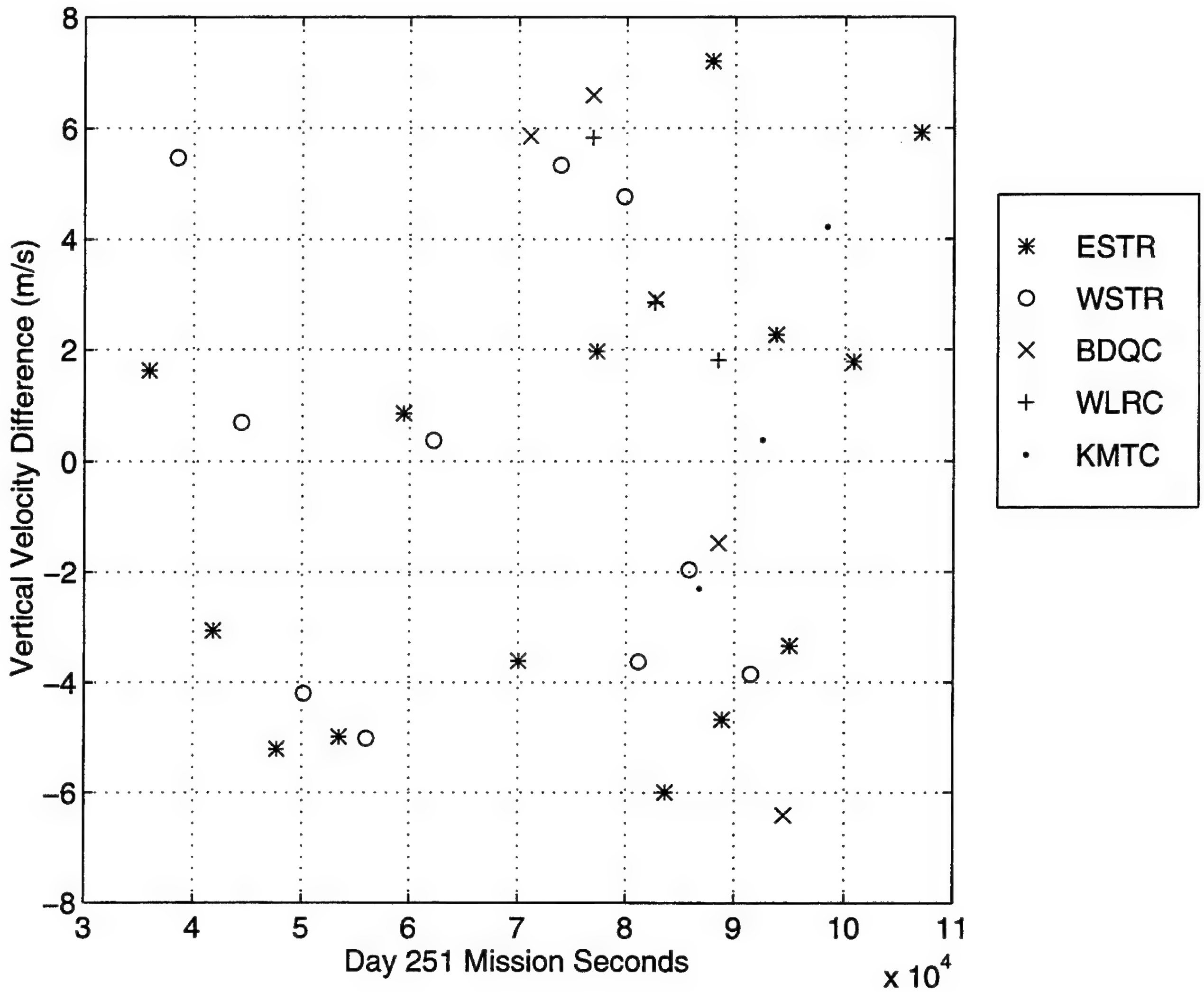

Day 251 Error Box and Position Differences in J2000 Coordinates
ESTR
WSTR
BDQC
WLRC
KMTC
1000
500
0
-500
-1000
Z Axis (m)
2000
1000
0
-1000
-2000
Y Axis (m)
-4000
-2000
0
2000
4000
X Axis (m)


150
100
50
0
−50
−100
−150
Vertical Position Difference (m)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

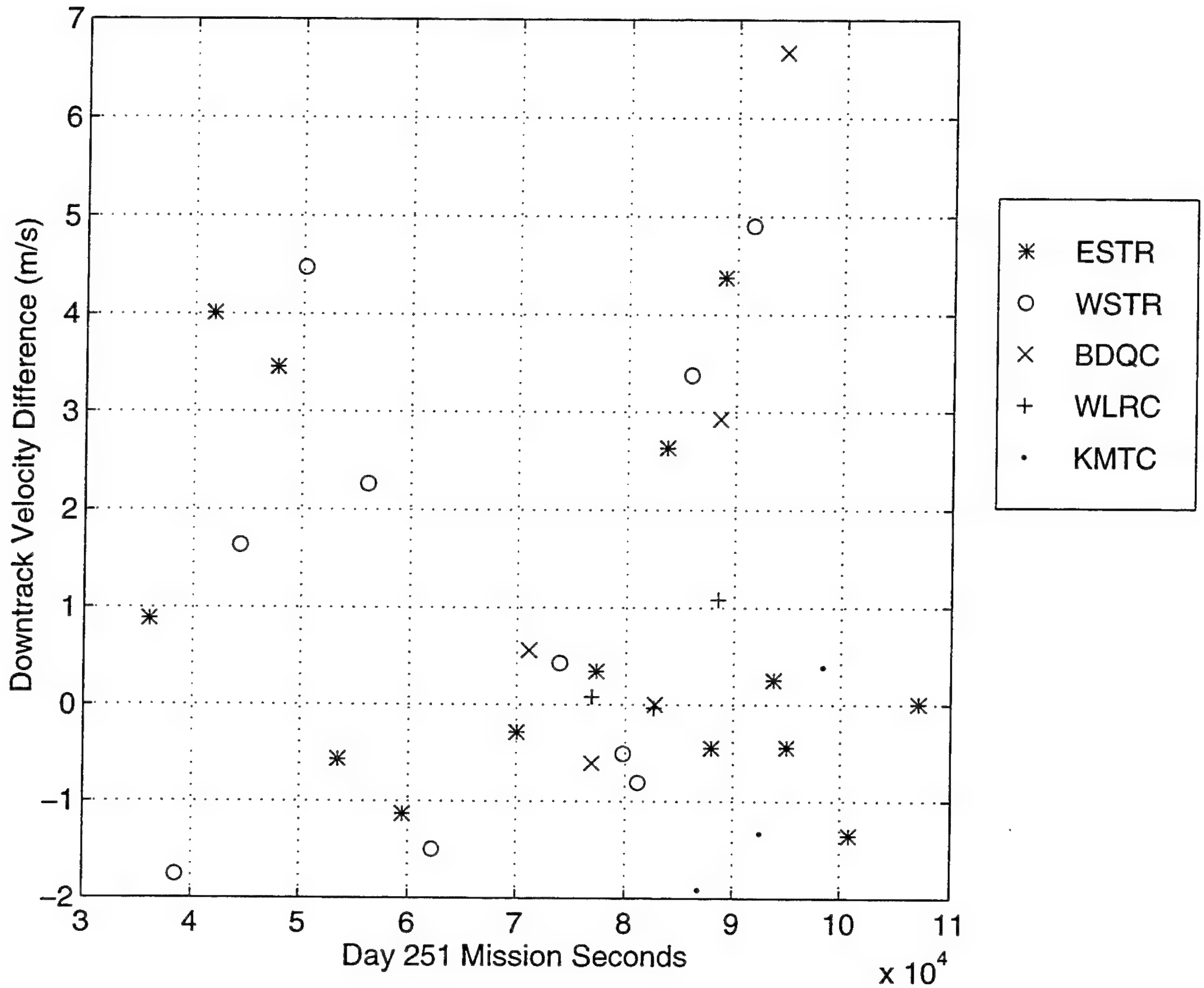


2000
1500
1000
500
0
−500
−1000
−1500
−2000
−2500
Downtrack Position Difference (m)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

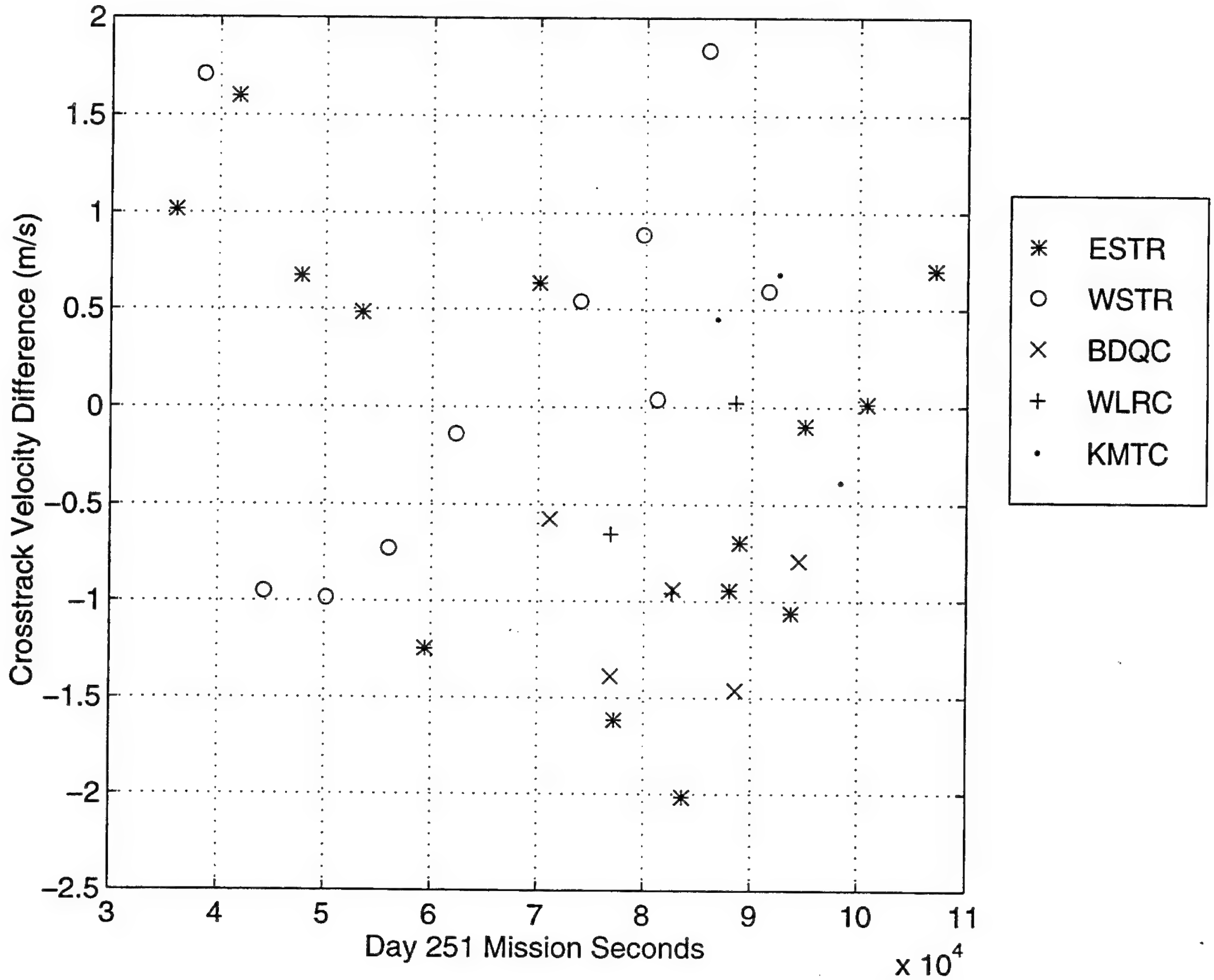

x 10^-10
10
5
0
−5
Crosstrack Position Difference (m)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC



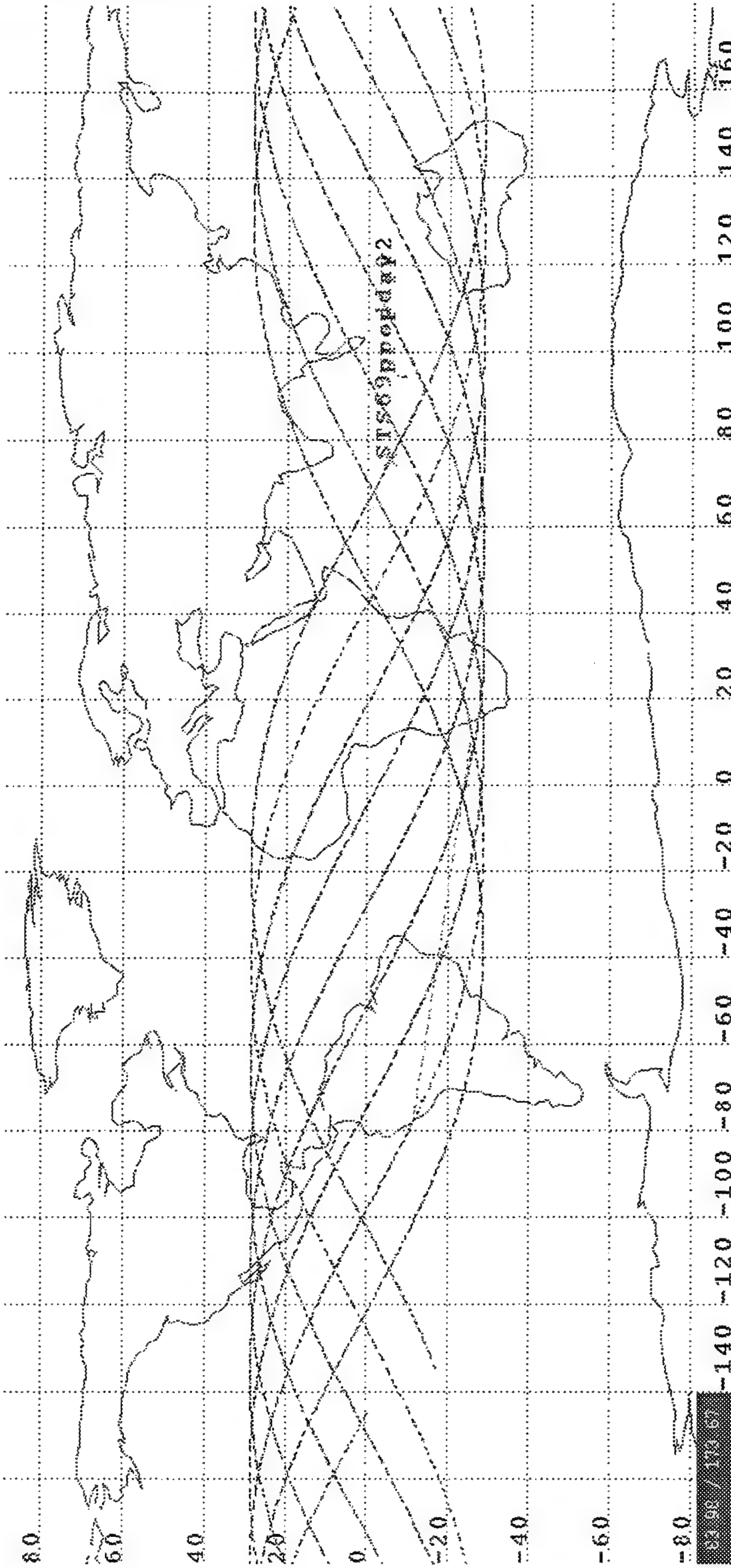
8
6
4
2
0
−2
−4
−6
−8
Vertical Velocity Difference (m/s)
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

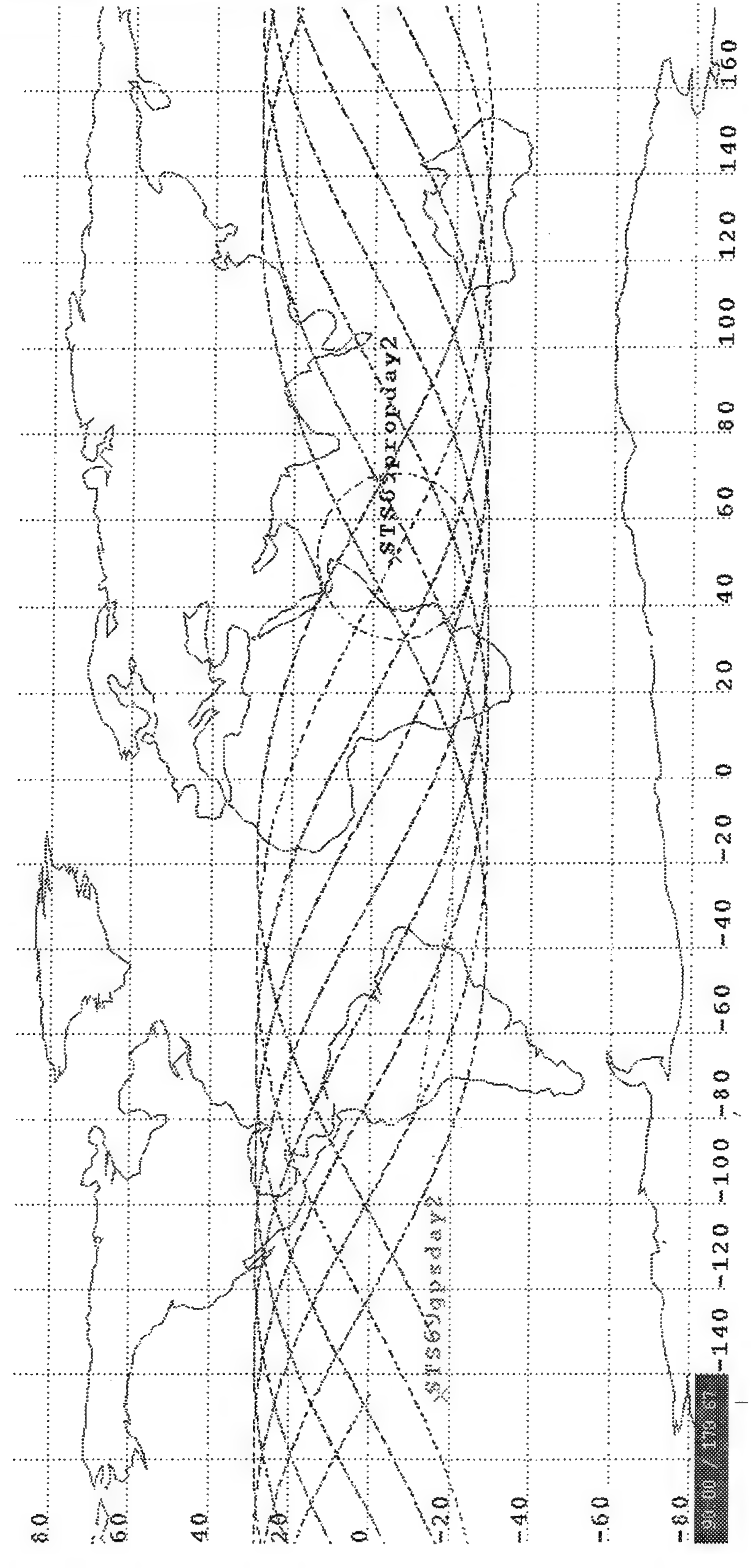


Downtrack Velocity Difference (m/s)
7
6
5
4
3
2
1
0
−1
−2
3
4
5
6
7
8
9
10
11
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

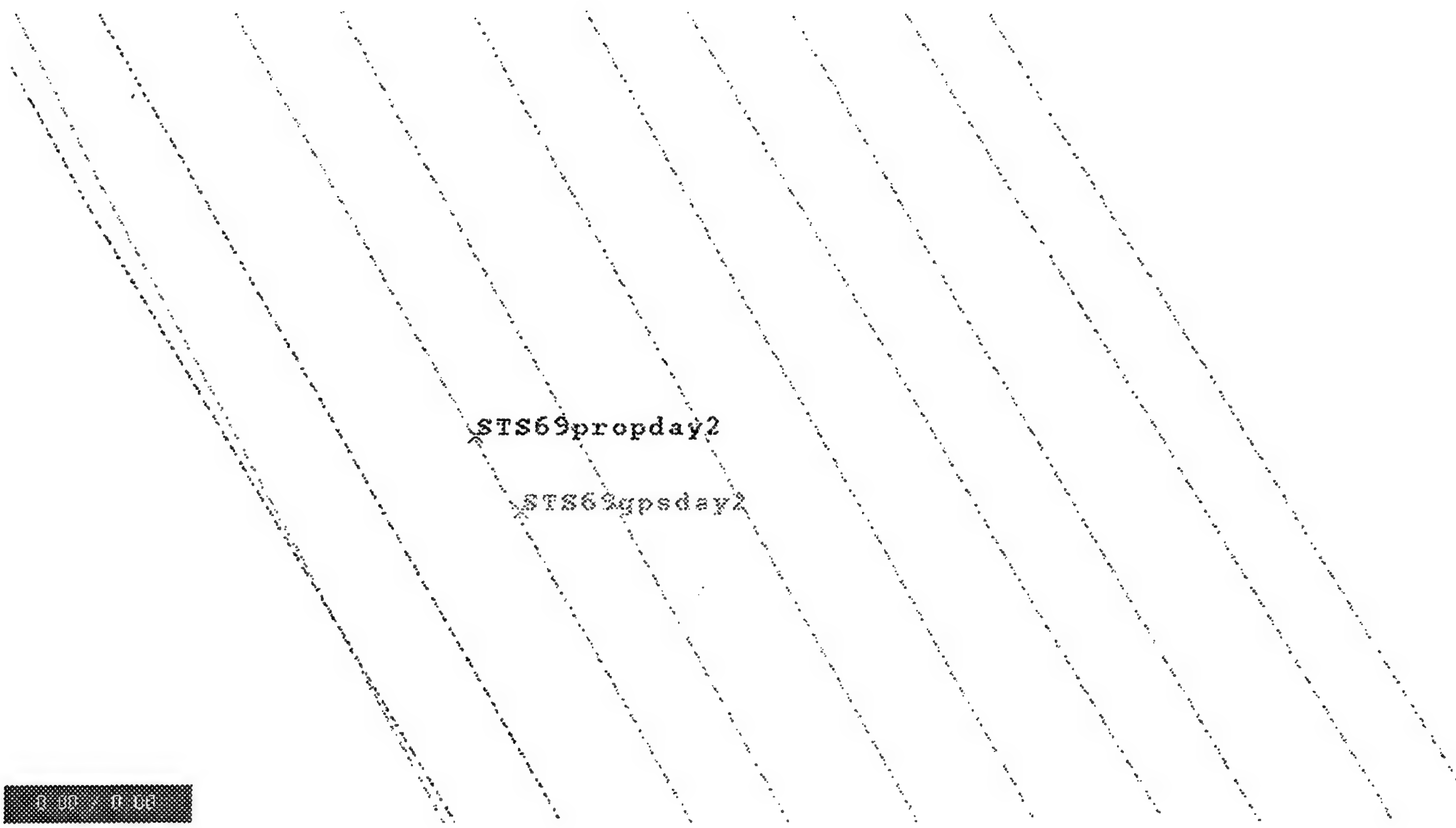

Crosstrack Velocity Difference (m/s)
Day 251 Mission Seconds
x 10^4
ESTR
WSTR
BDQC
WLRC
KMTC

APPENDIX L. DAY 252 STK PLOTS


STS69propday2
80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

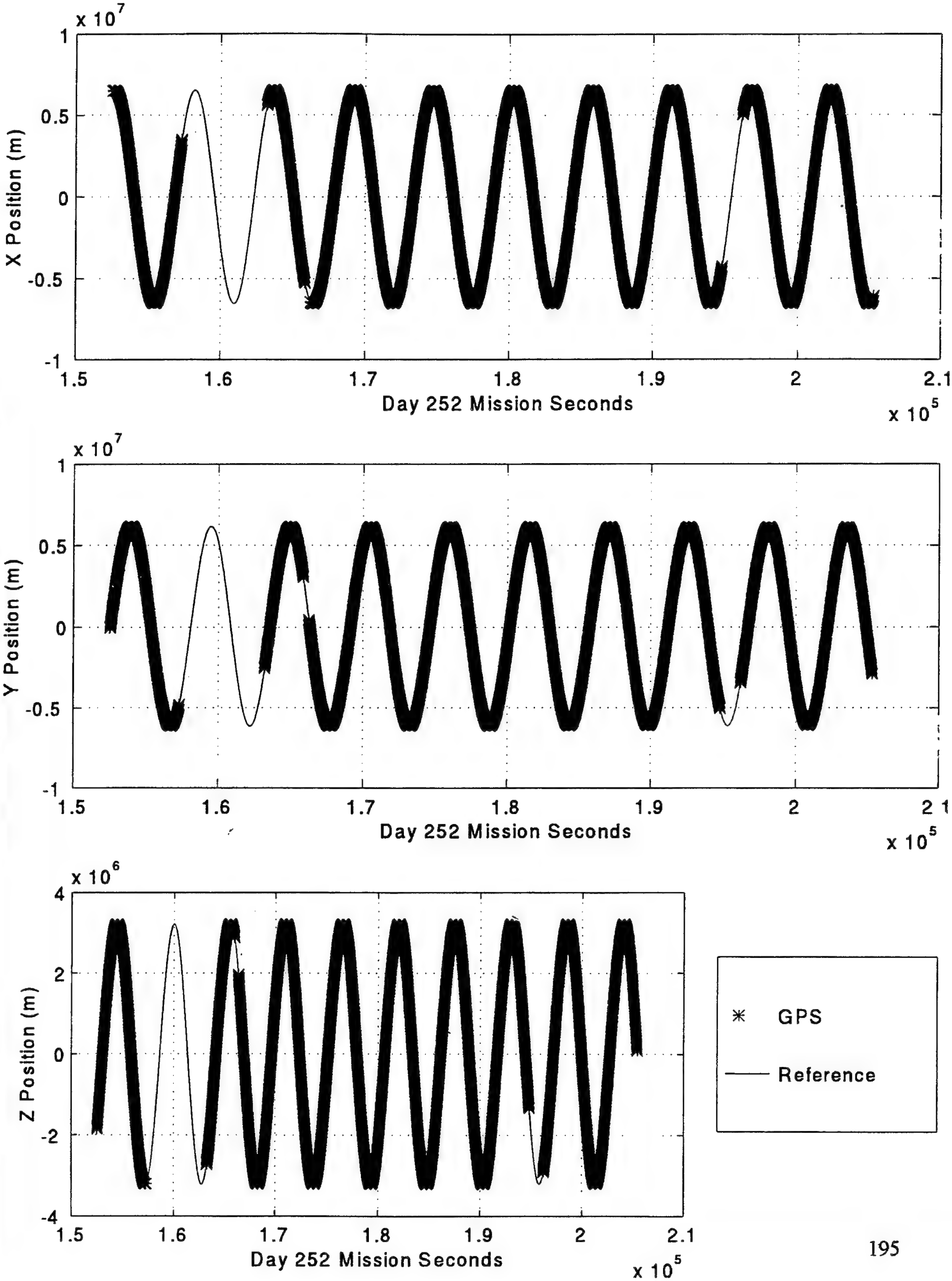

STS65propday2
STS65gpsday2
80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160


STS69propdxy2
0 00 / 0 00

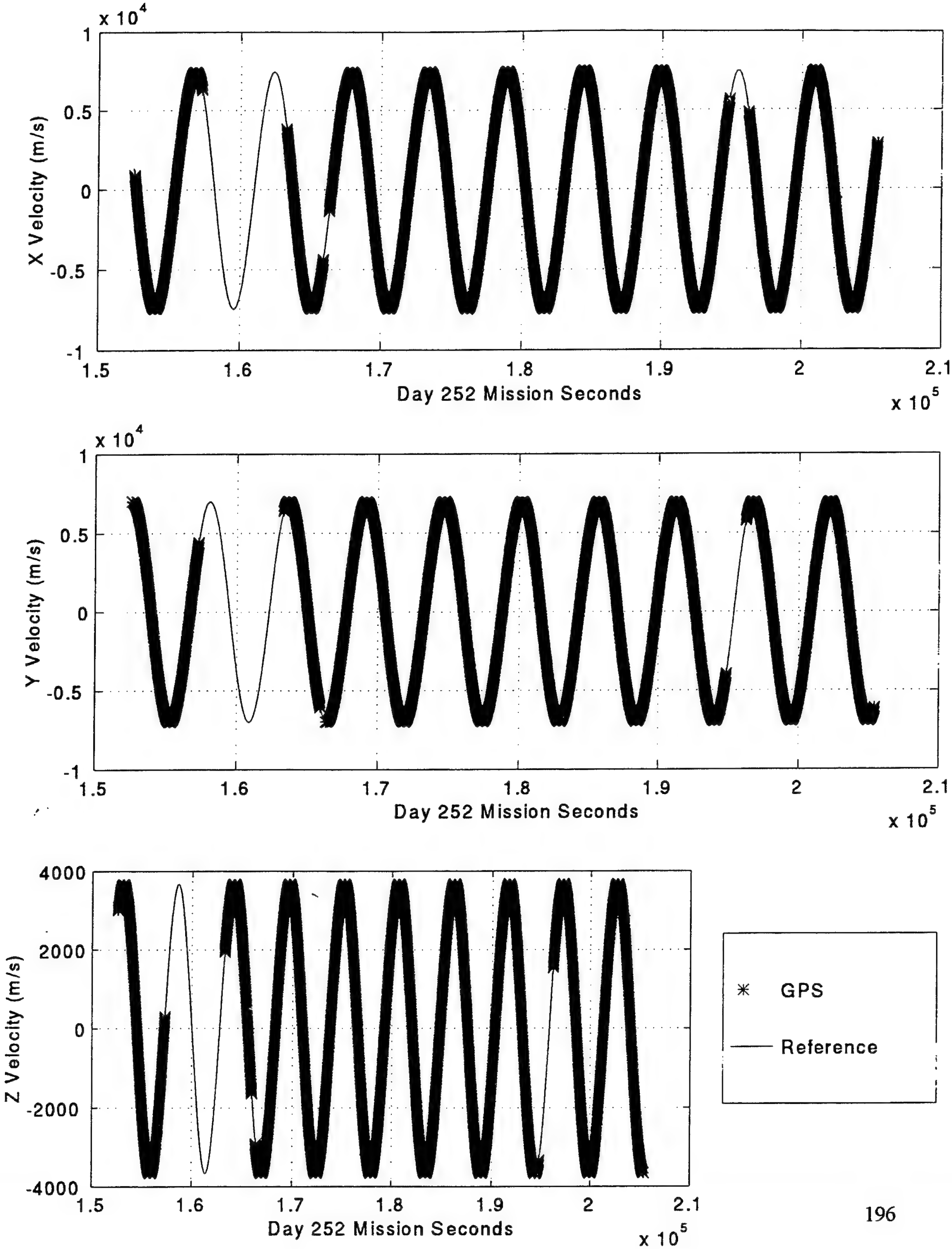


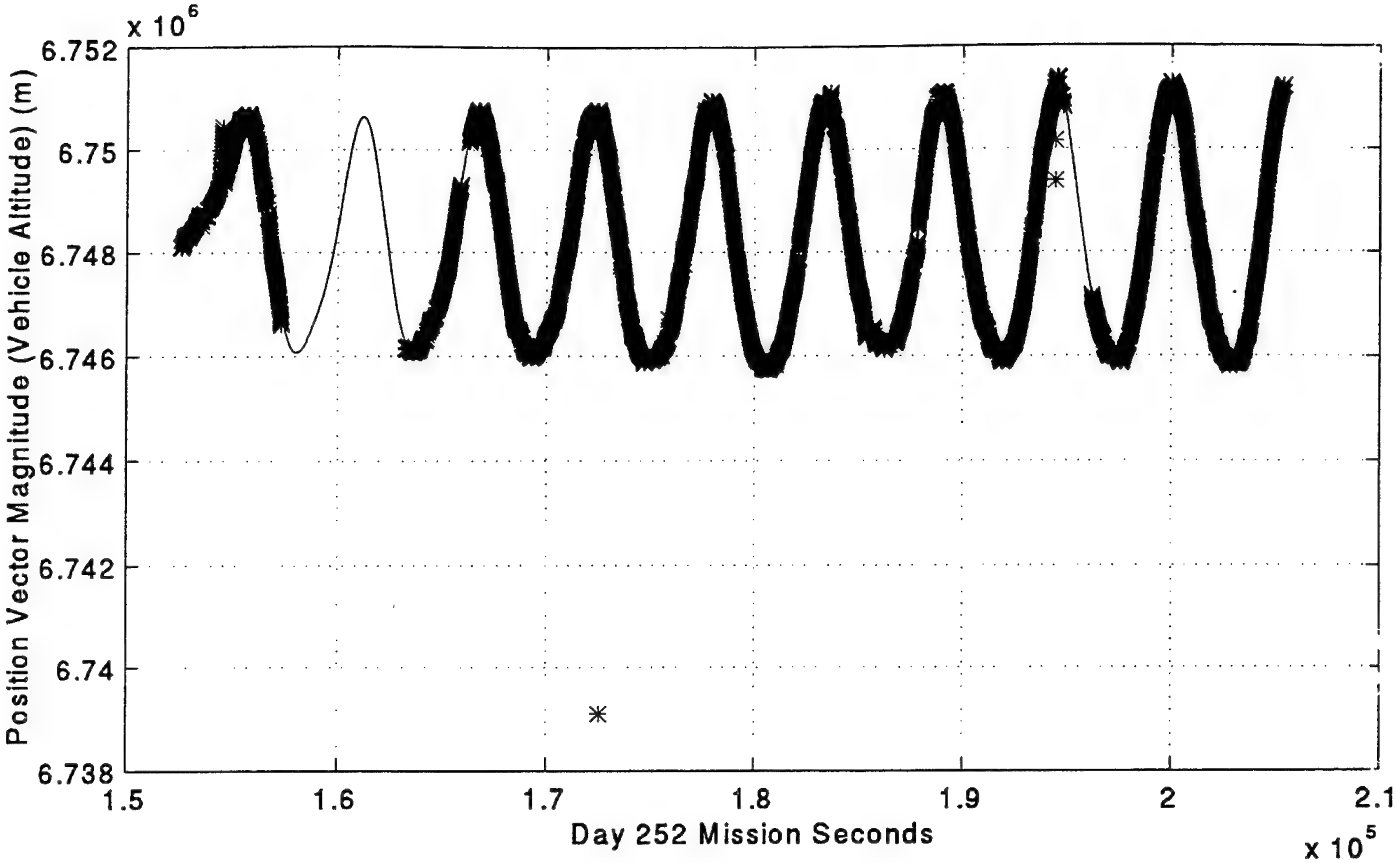
STS69propday2
STS69gpsday2

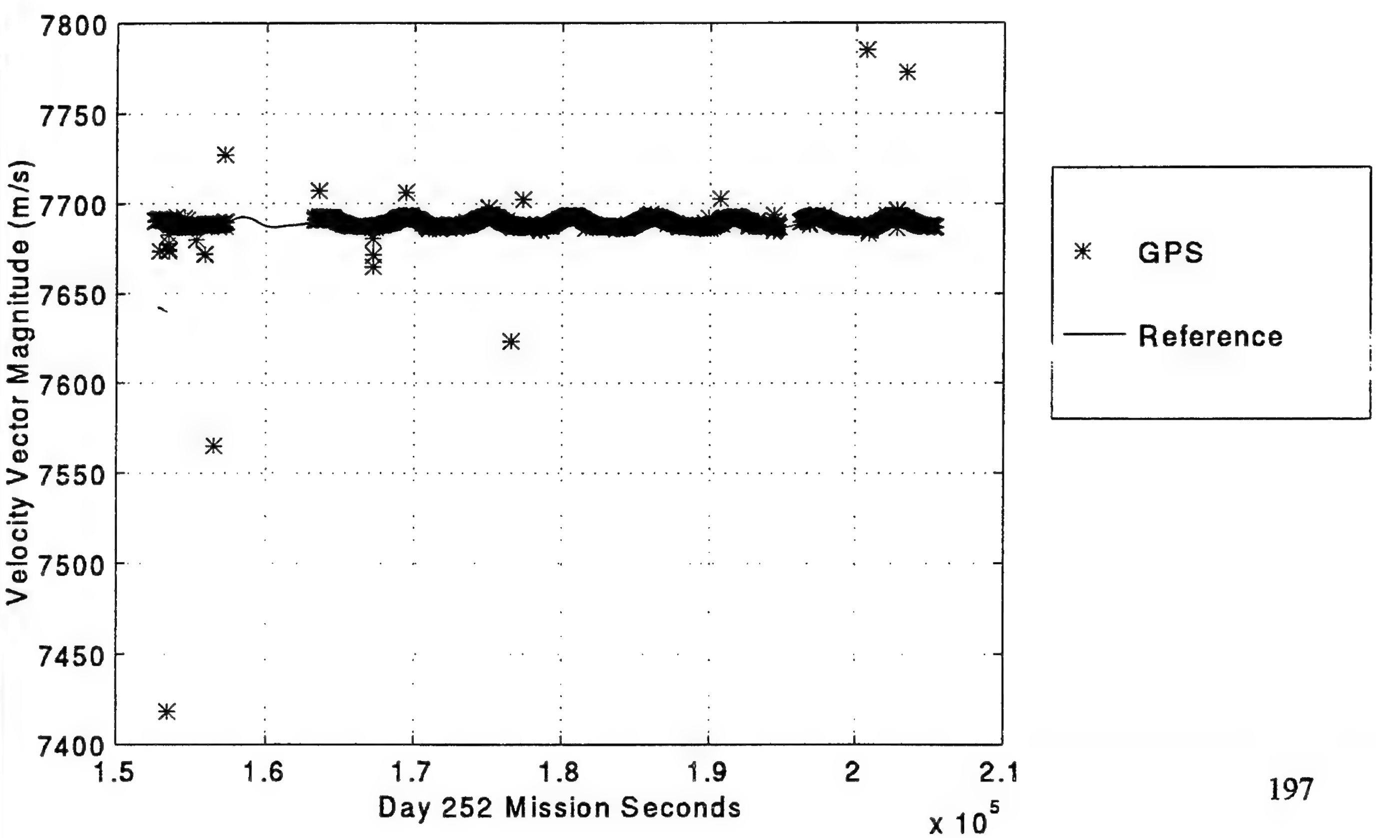
APPENDIX M. DAY 252 MATLAB PLOTS



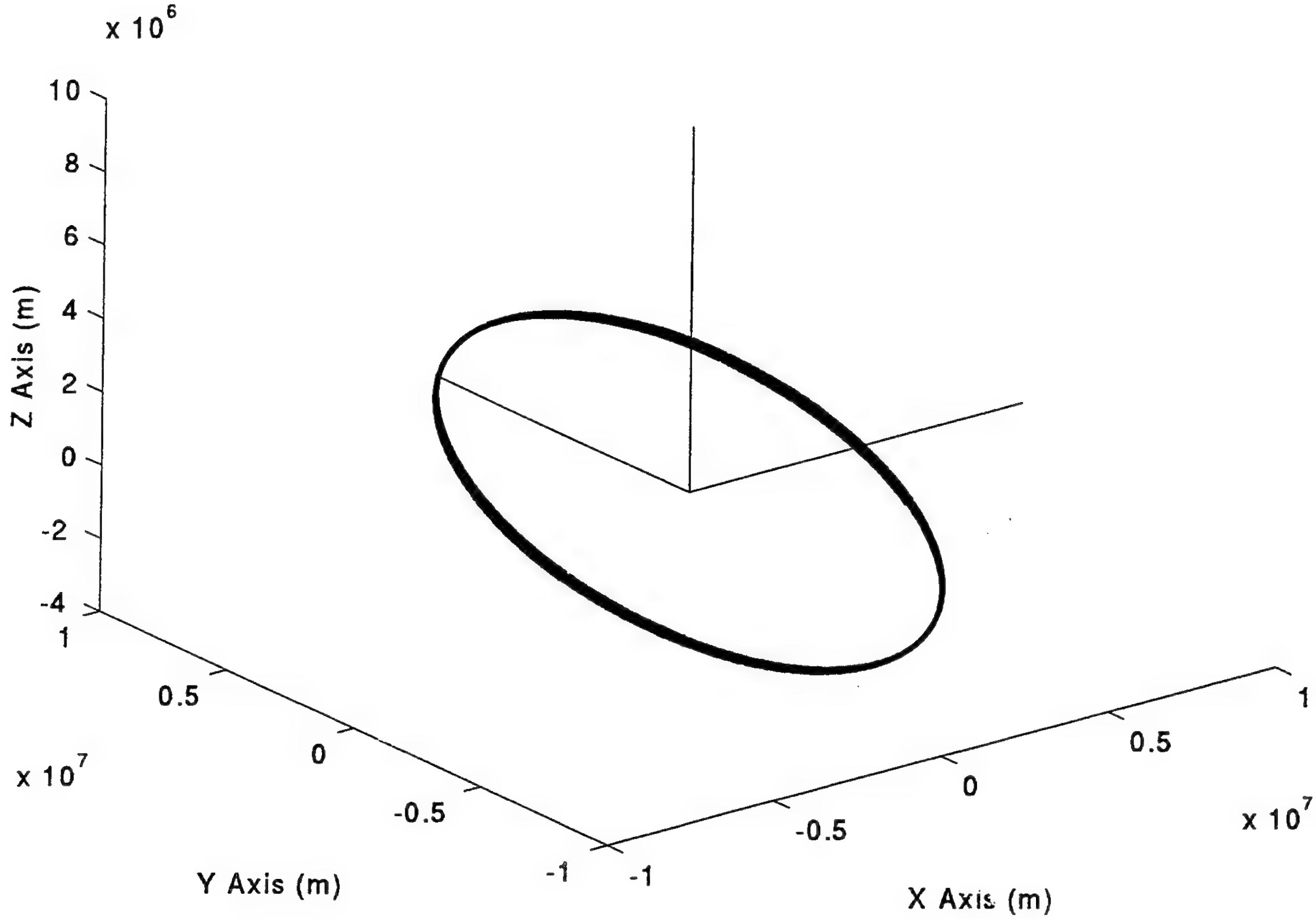
x 10^7
X Position (m)
1
0.5
0
-0.5
-1
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
x 10^7
Y Position (m)
1
0.5
0
-0.5
-1
1.5
1.6
1.7
1.8
1.9
2
2 1
Day 252 Mission Seconds
x 10^5
x 10^6
Z Position (m)
4
2
0
-2
-4
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
GPS
Reference

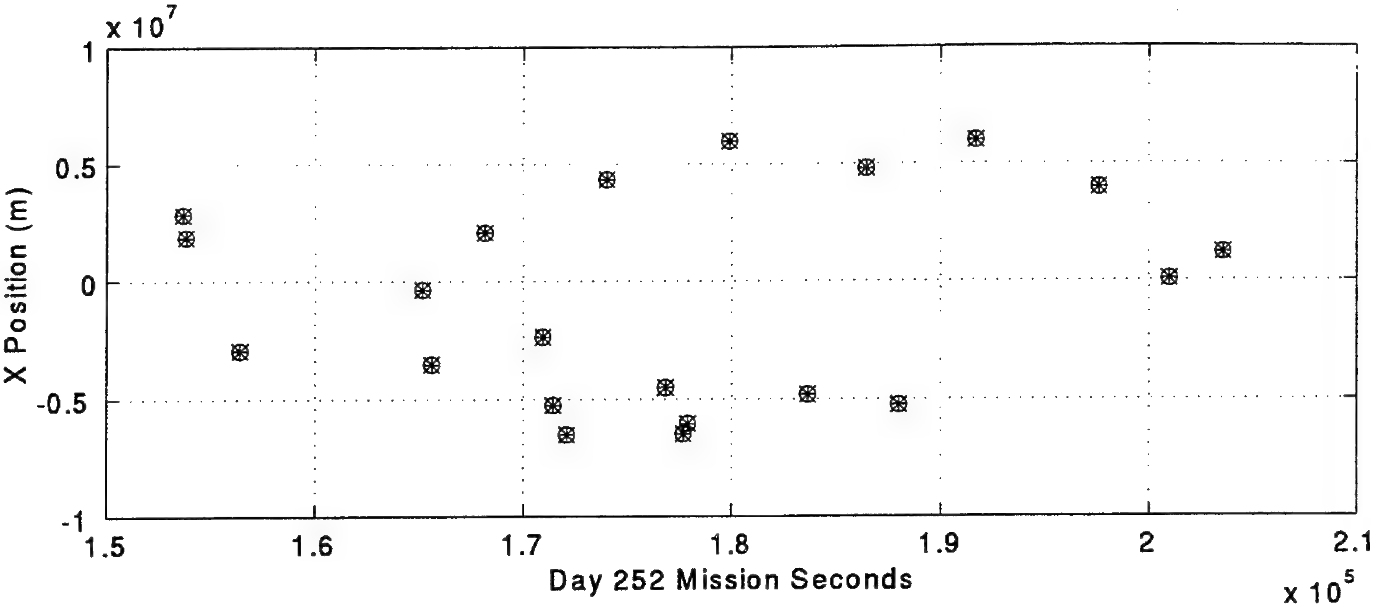

x 10^4
1
0.5
0
-0.5
-1
X Velocity (m/s)
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
x 10^4
1
0.5
0
-0.5
-1
Y Velocity (m/s)
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
4000
2000
0
-2000
-4000
Z Velocity (m/s)
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
GPS
Reference


x 10^6
6.752
6.75
6.748
6.746
6.744
6.742
6.74
6.738
Position Vector Magnitude (Vehicle Altitude) (m)
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5

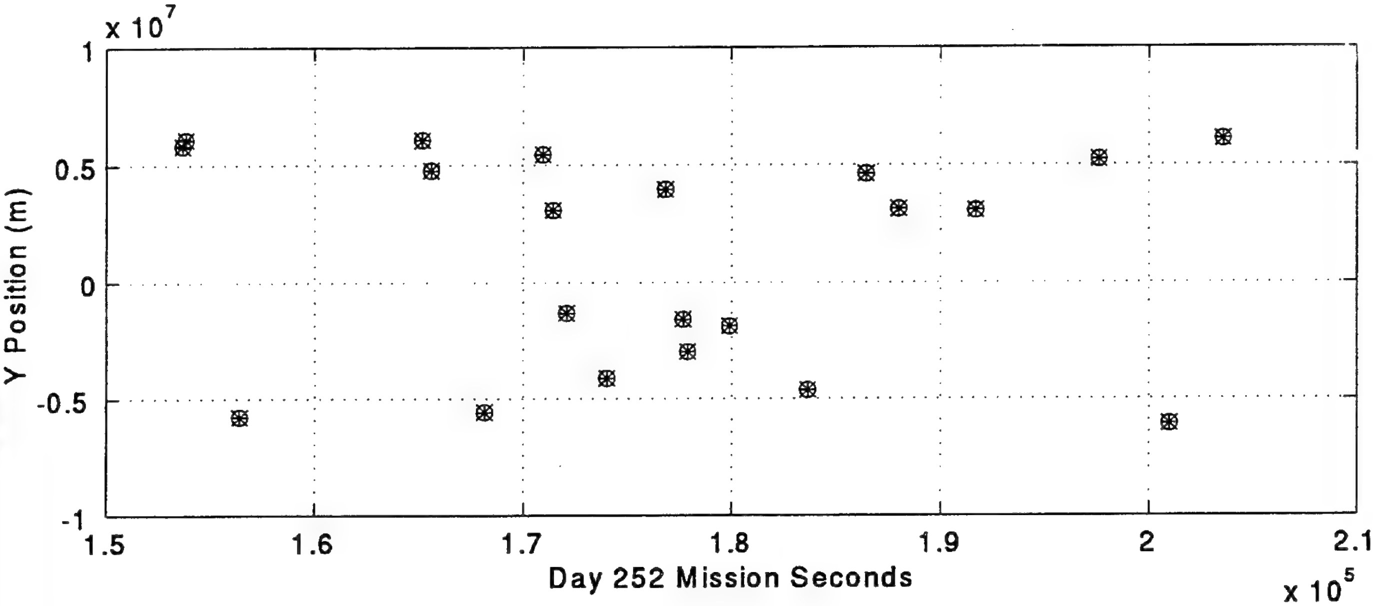

7800
7750
7700
7650
7600
7550
7500
7450
7400
Velocity Vector Magnitude (m/s)
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
GPS
Reference

GPS Orbit for Day 252 in J2000 Coordinates

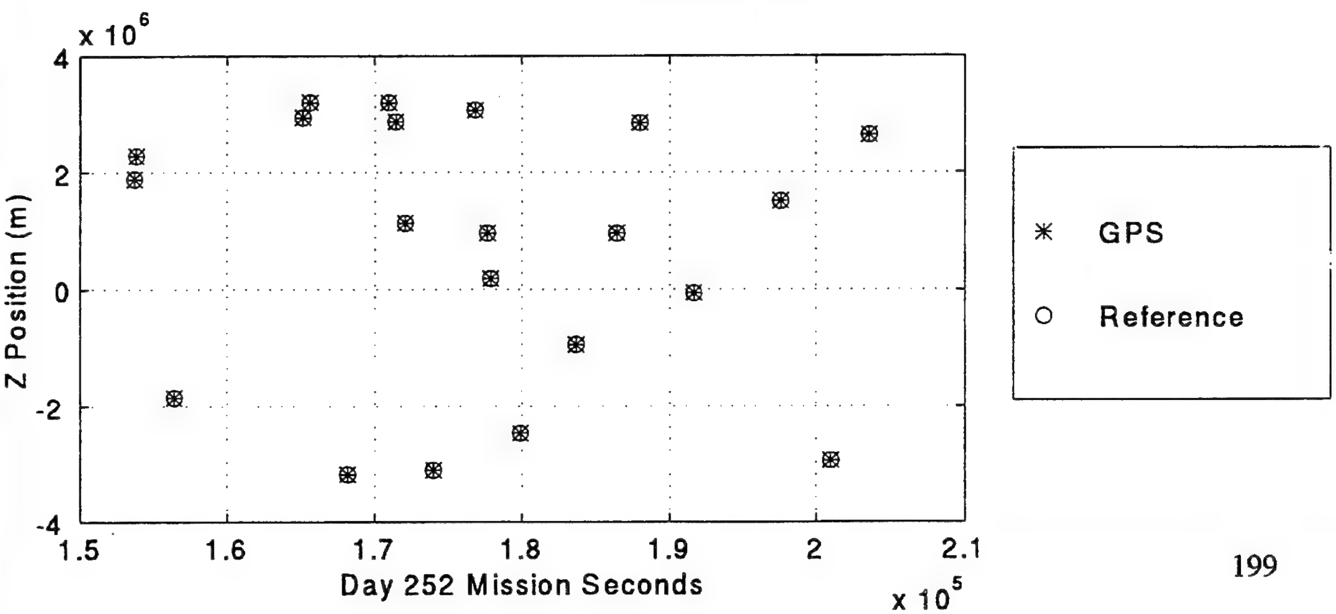




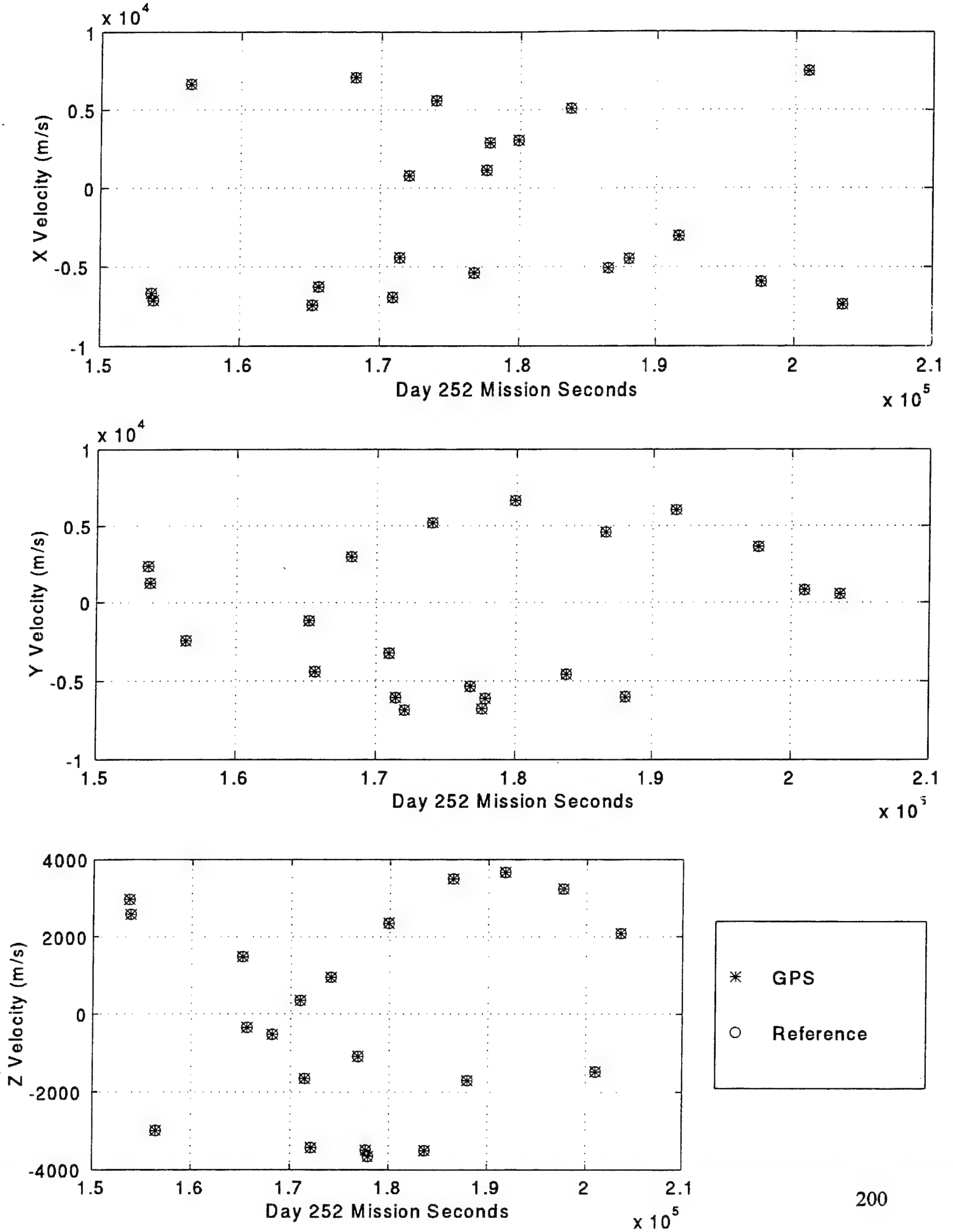
x 10^7
X Position (m)
Day 252 Mission Seconds
x 10^5



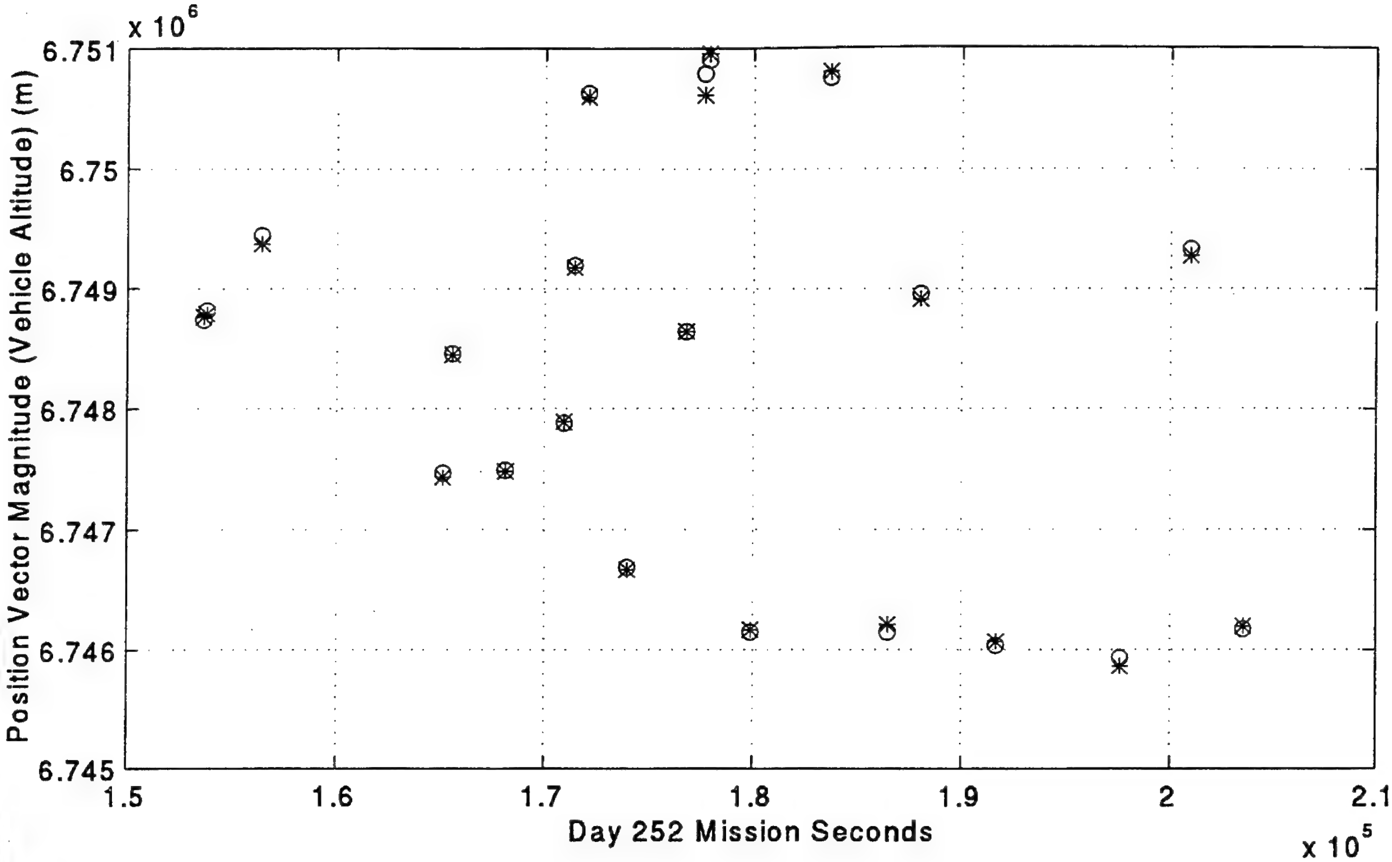
x 10^7
Y Position (m)
Day 252 Mission Seconds
x 10^5

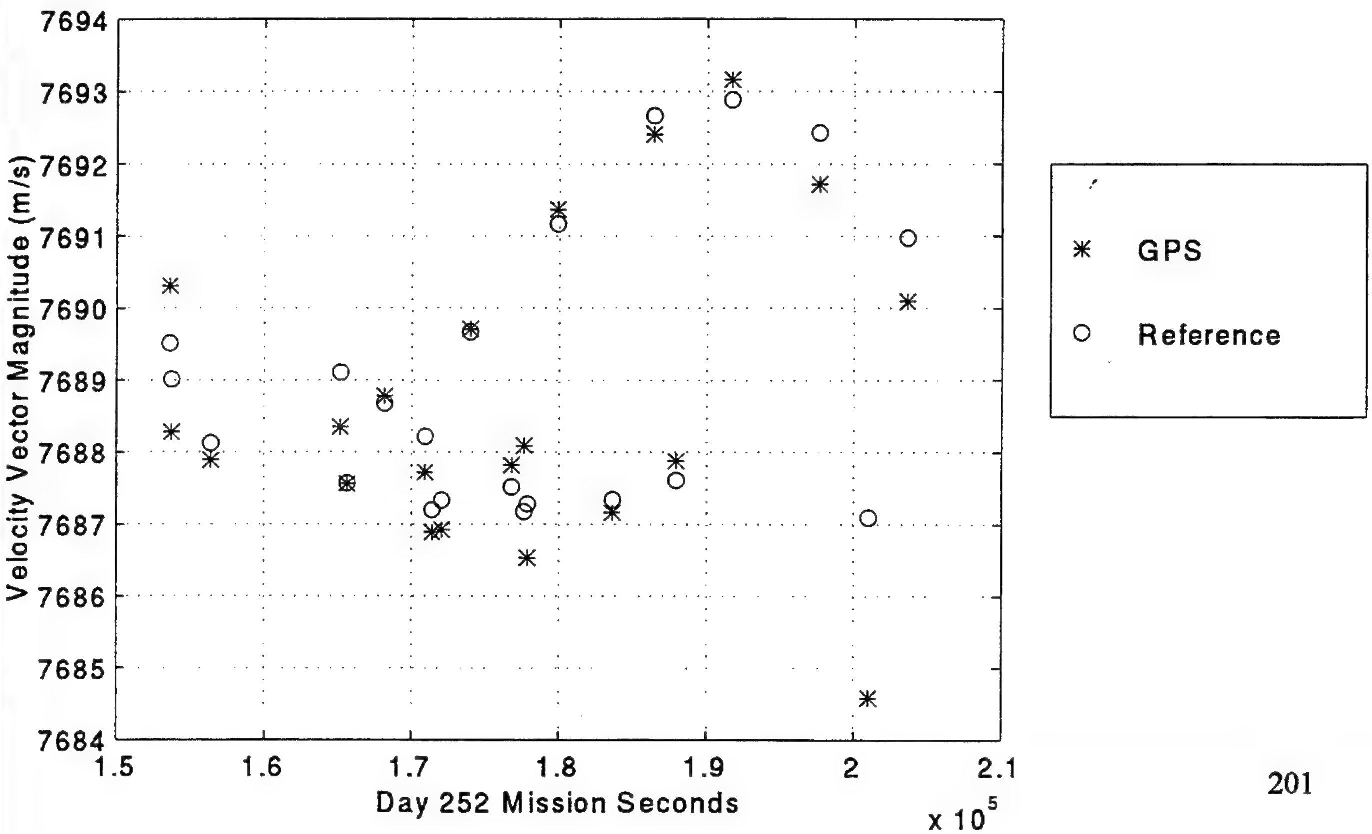


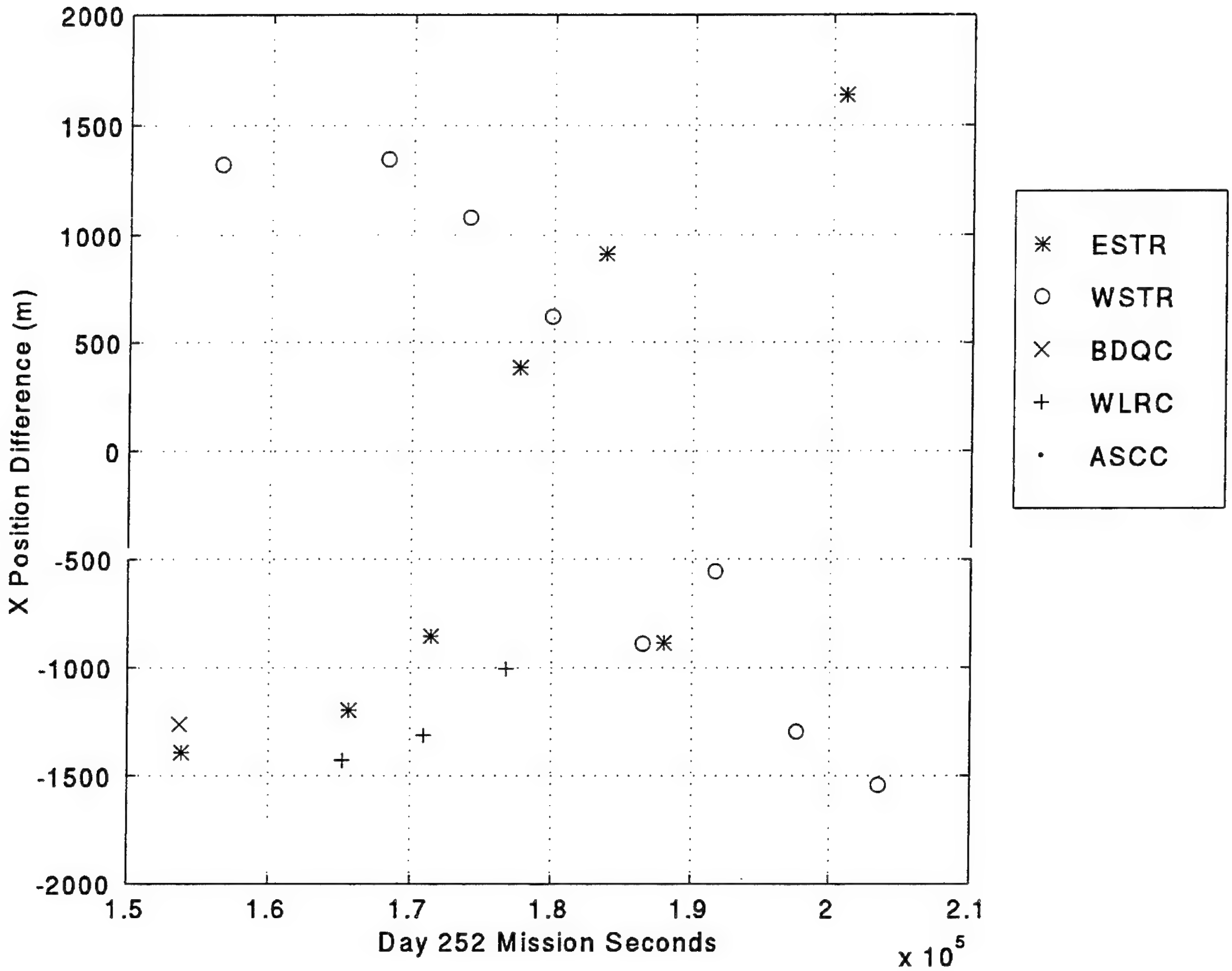
x 10^6
Z Position (m)
Day 252 Mission Seconds
x 10^5
GPS
Reference



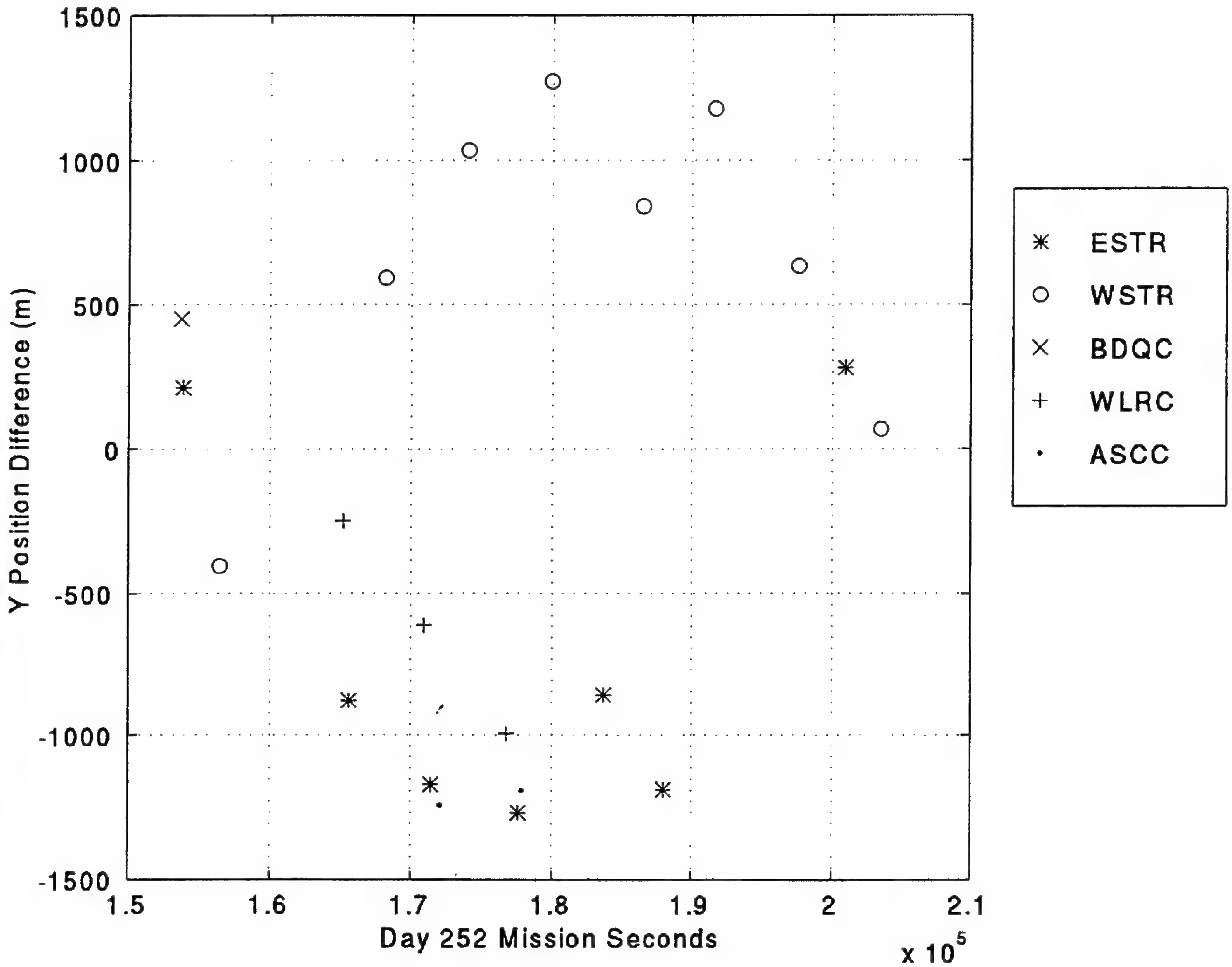
x 10^4
X Velocity (m/s)
Day 252 Mission Seconds
x 10^5
Y Velocity (m/s)
Z Velocity (m/s)
GPS
Reference


x 10^6
6.751
6.75
6.749
6.748
6.747
6.746
6.745
Position Vector Magnitude (Vehicle Altitude) (m)
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5

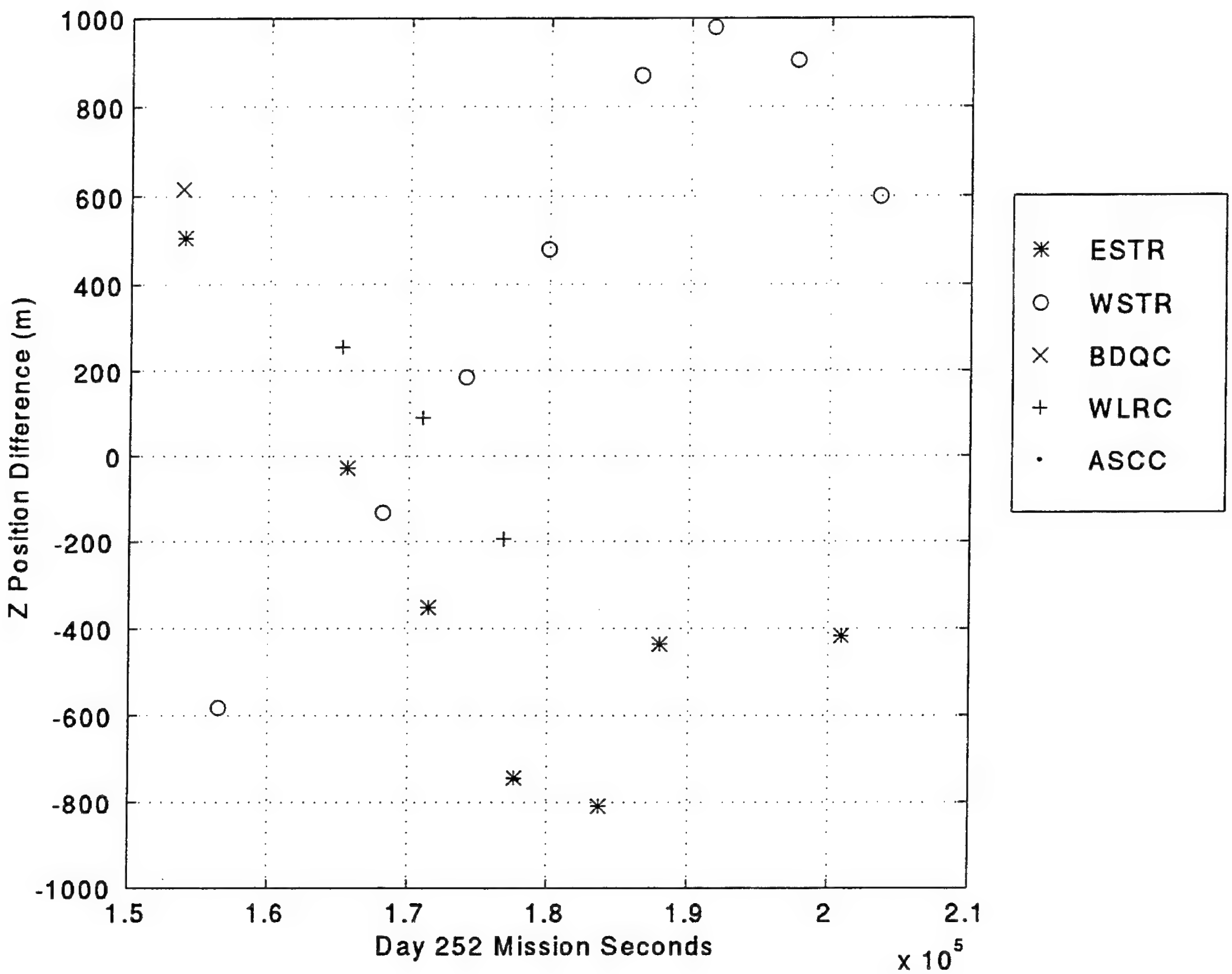

7694
7693
7692
7691
7690
7689
7688
7687
7686
7685
7684
Velocity Vector Magnitude (m/s)
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
GPS
Reference



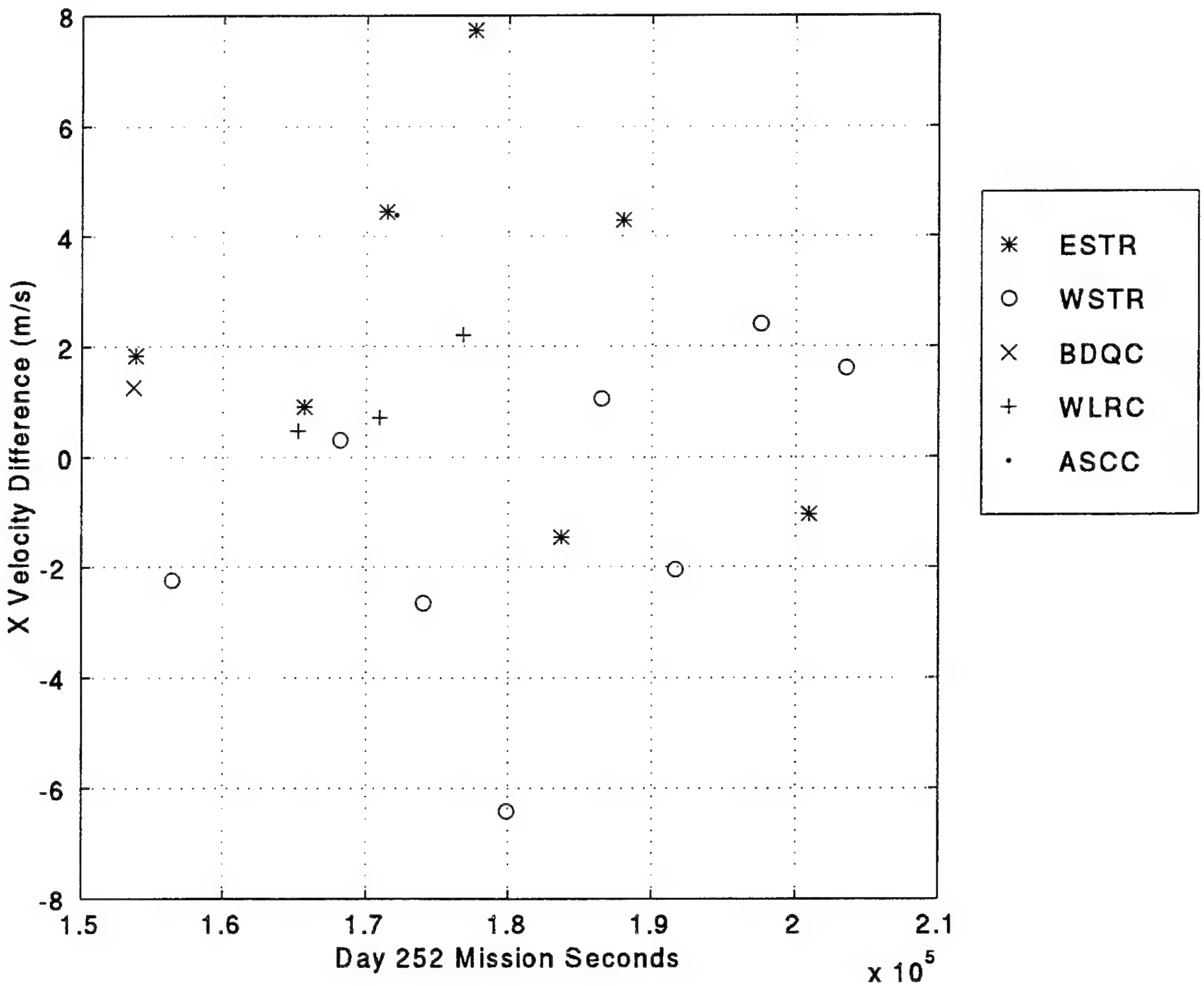
2000
1500
1000
500
0
-500
-1000
-1500
-2000
1.5
1.6
1.7
1.8
1.9
2
2.1
x 10^5
Day 252 Mission Seconds
X Position Difference (m)
ESTR
WSTR
BDQC
WLRC
ASCC



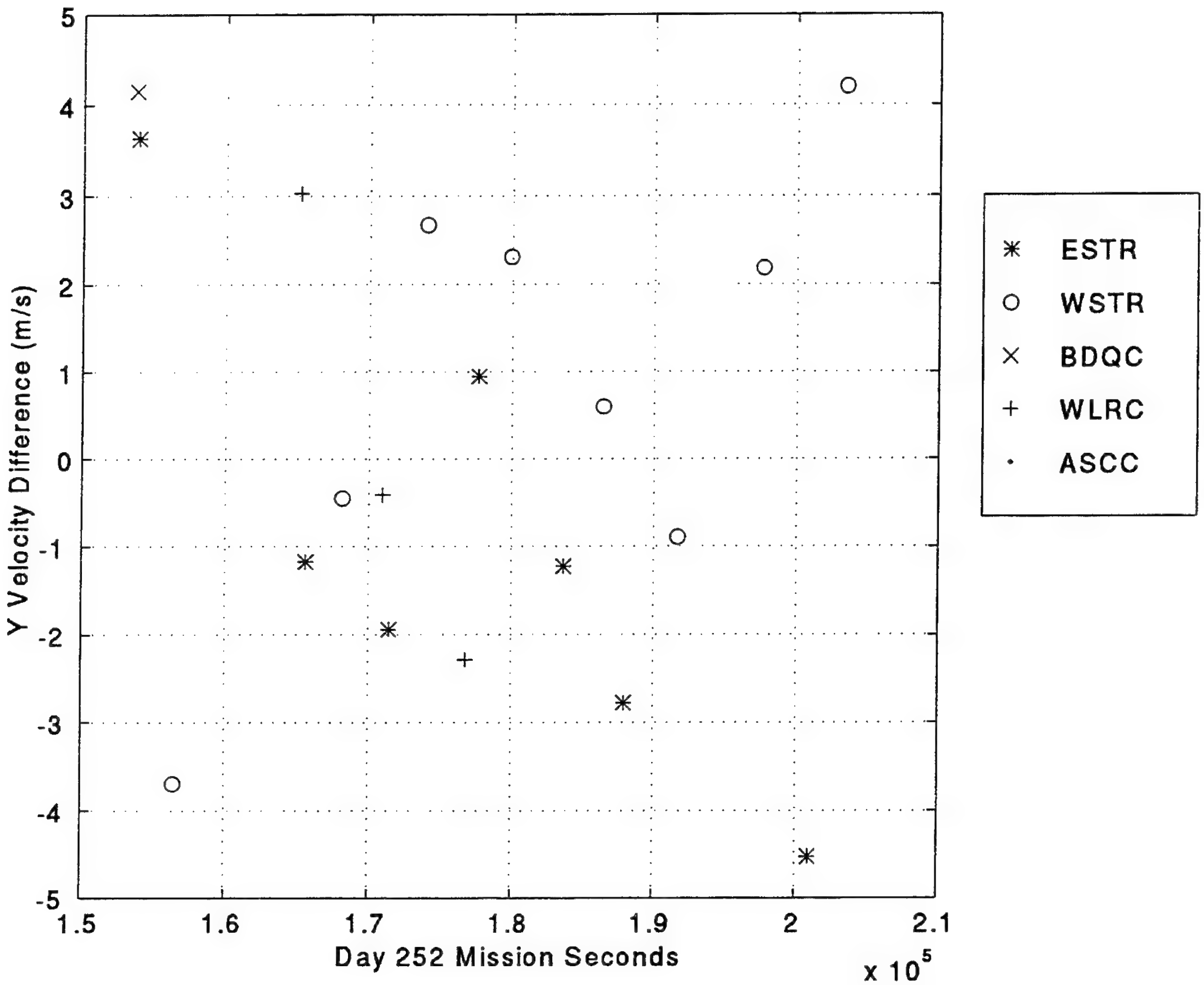
1500
1000
500
0
-500
-1000
-1500
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
Y Position Difference (m)
ESTR
WSTR
BDQC
WLRC
ASCC

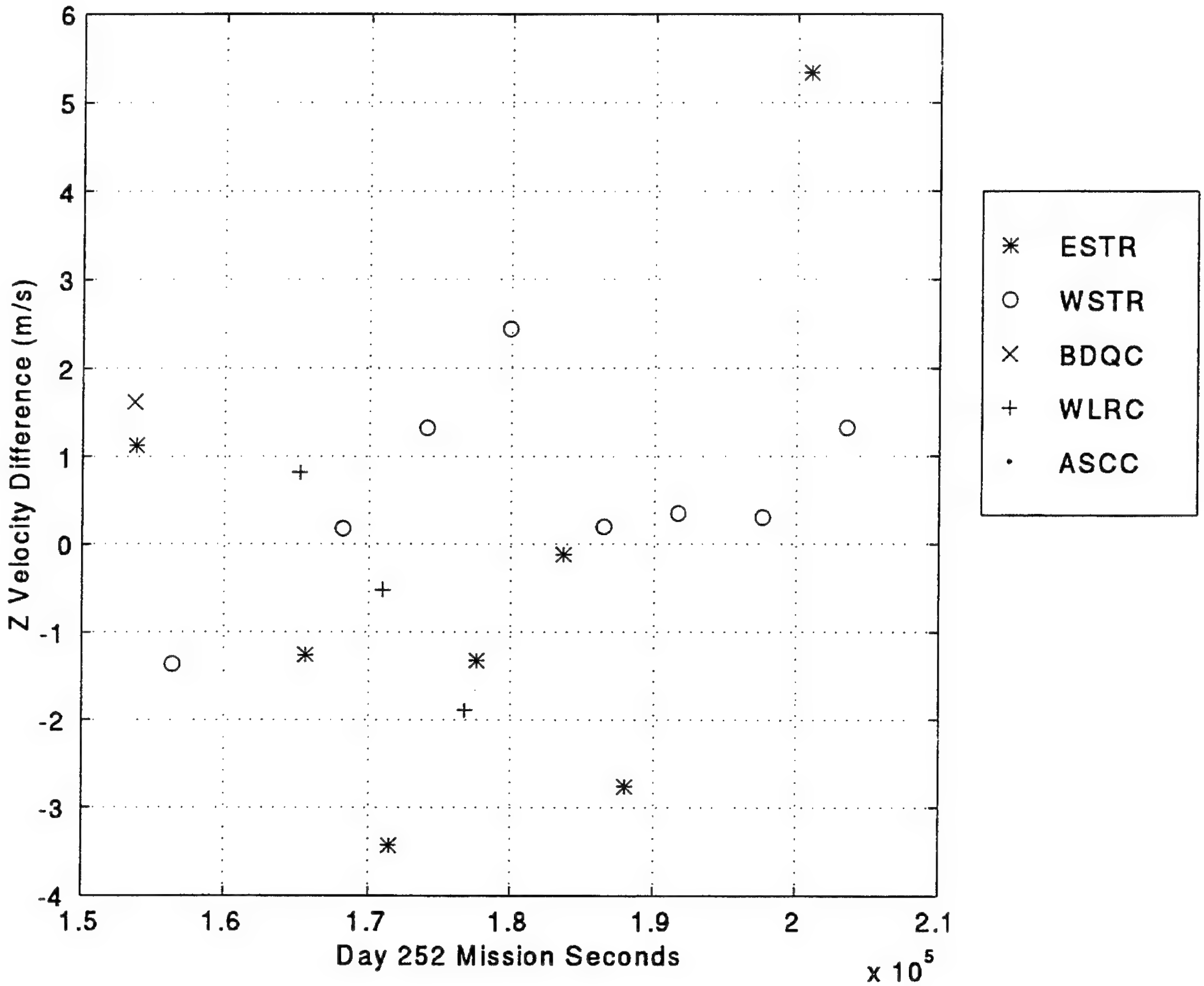


1000
800
600
400
200
0
-200
-400
-600
-800
-1000
1.5
1.6
1.7
1.8
1.9
2
2.1
Z Position Difference (m)
Day 252 Mission Seconds
x 10^5
ESTR
WSTR
BDQC
WLRC
ASCC

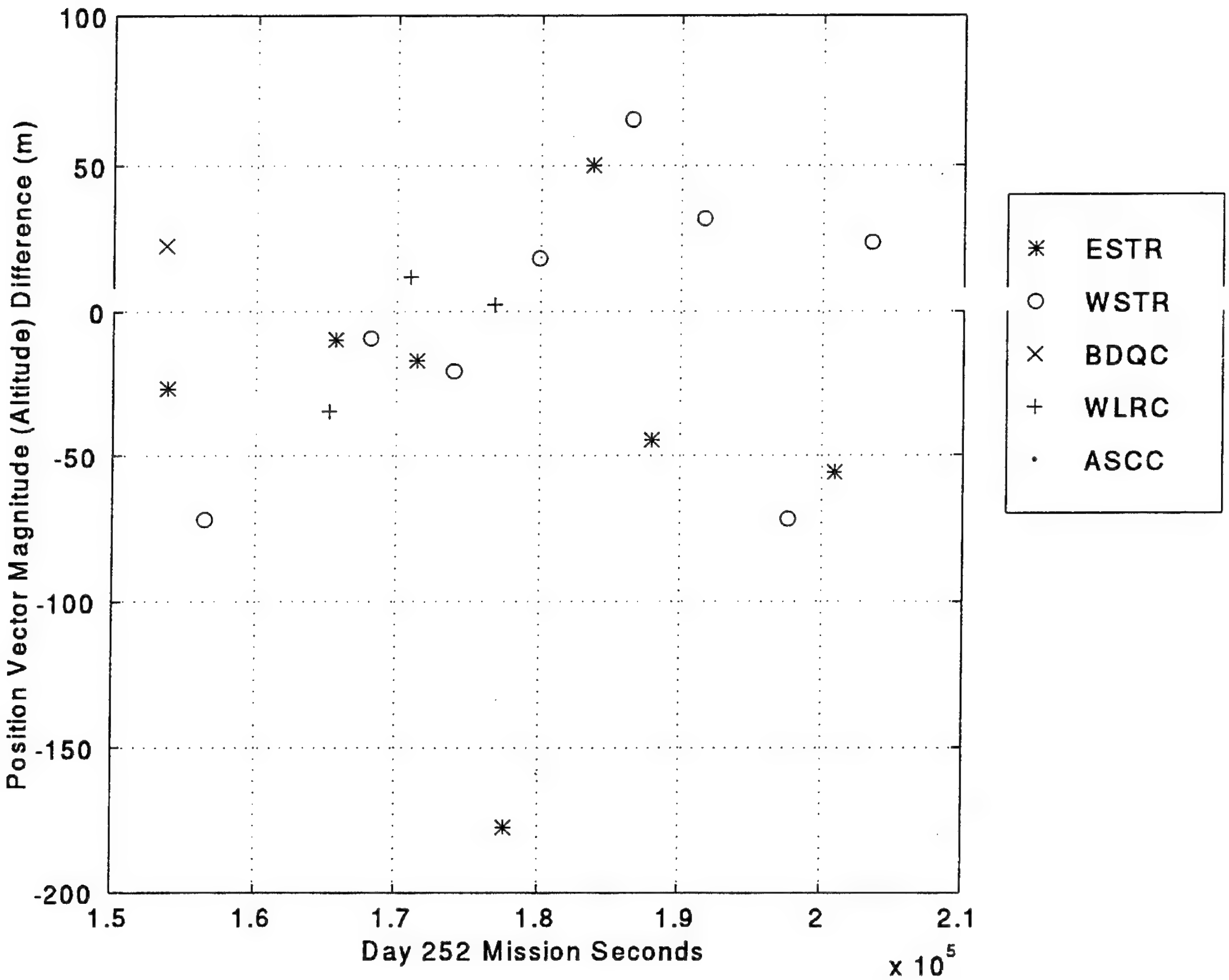


X Velocity Difference (m/s)
Day 252 Mission Seconds
x 10^5
8
6
4
2
0
-2
-4
-6
-8
1.5
1.6
1.7
1.8
1.9
2
2.1
ESTR
WSTR
BDQC
WLRC
ASCC

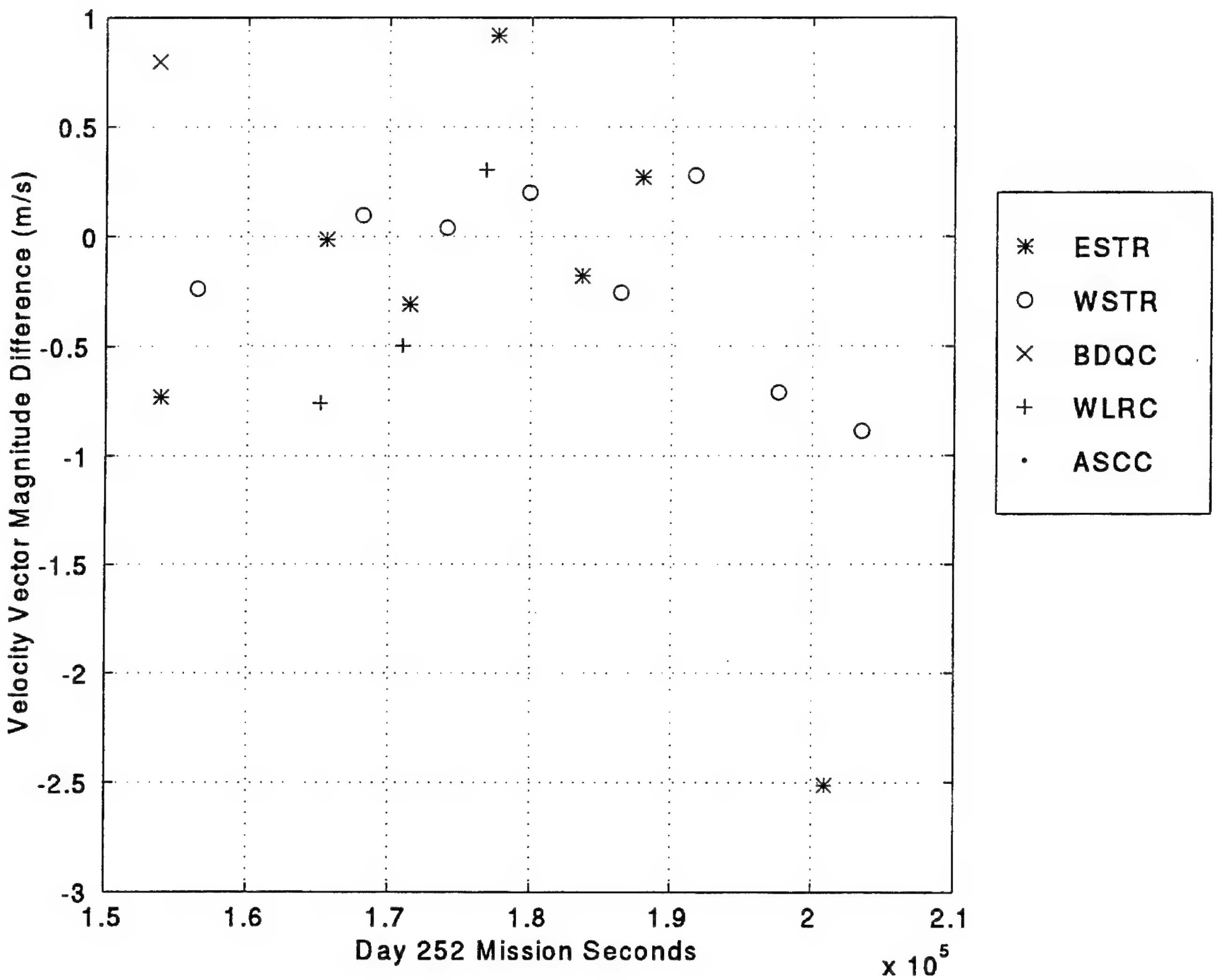

Y Velocity Difference (m/s)
Day 252 Mission Seconds
x 10^5
5
4
3
2
1
0
-1
-2
-3
-4
-5
1.5
1.6
1.7
1.8
1.9
2
2.1
ESTR
WSTR
BDQC
WLRC
ASCC



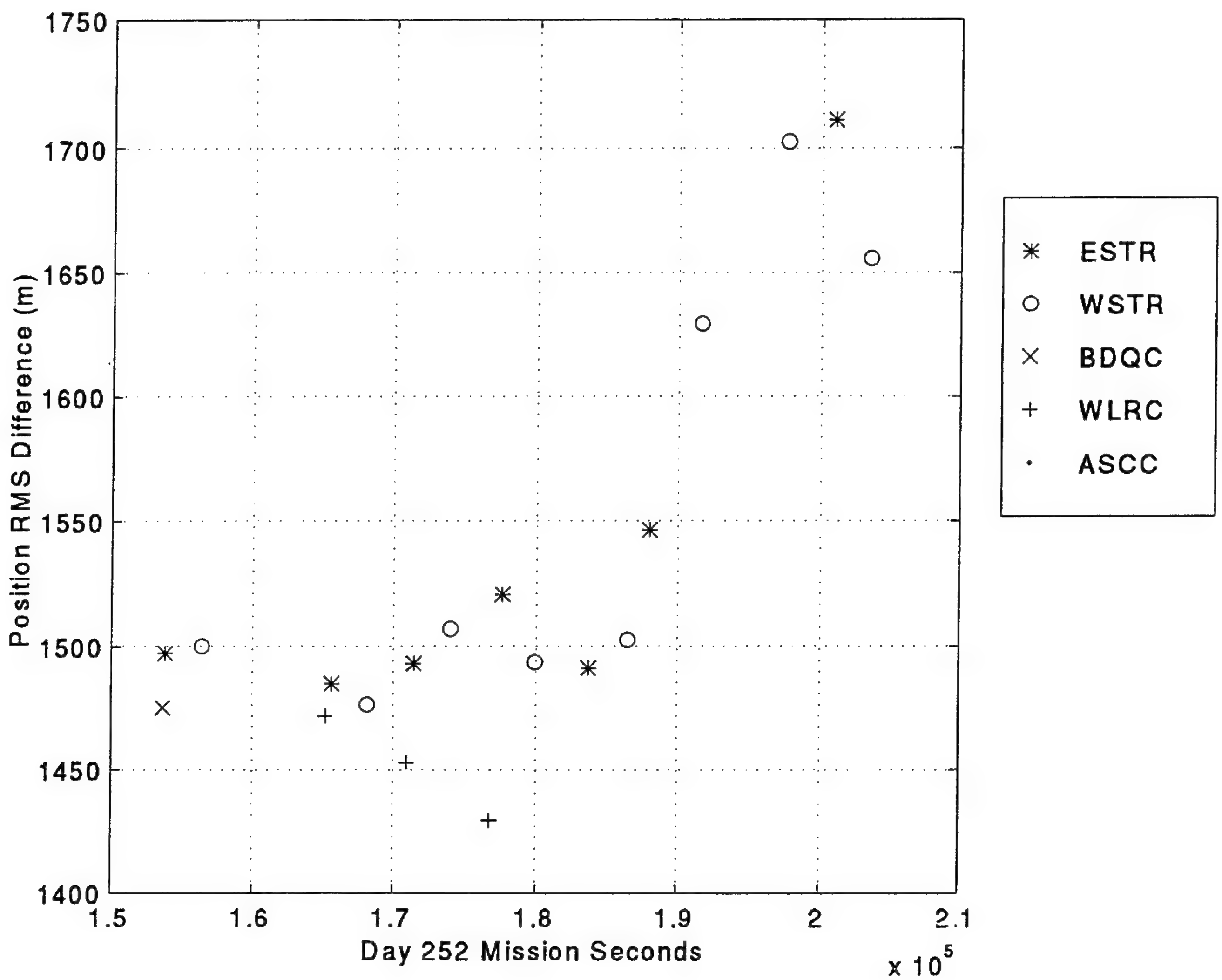
6
5
4
3
2
1
0
-1
-2
-3
-4
Z Velocity Difference (m/s)
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
ESTR
WSTR
BDQC
WLRC
ASCC



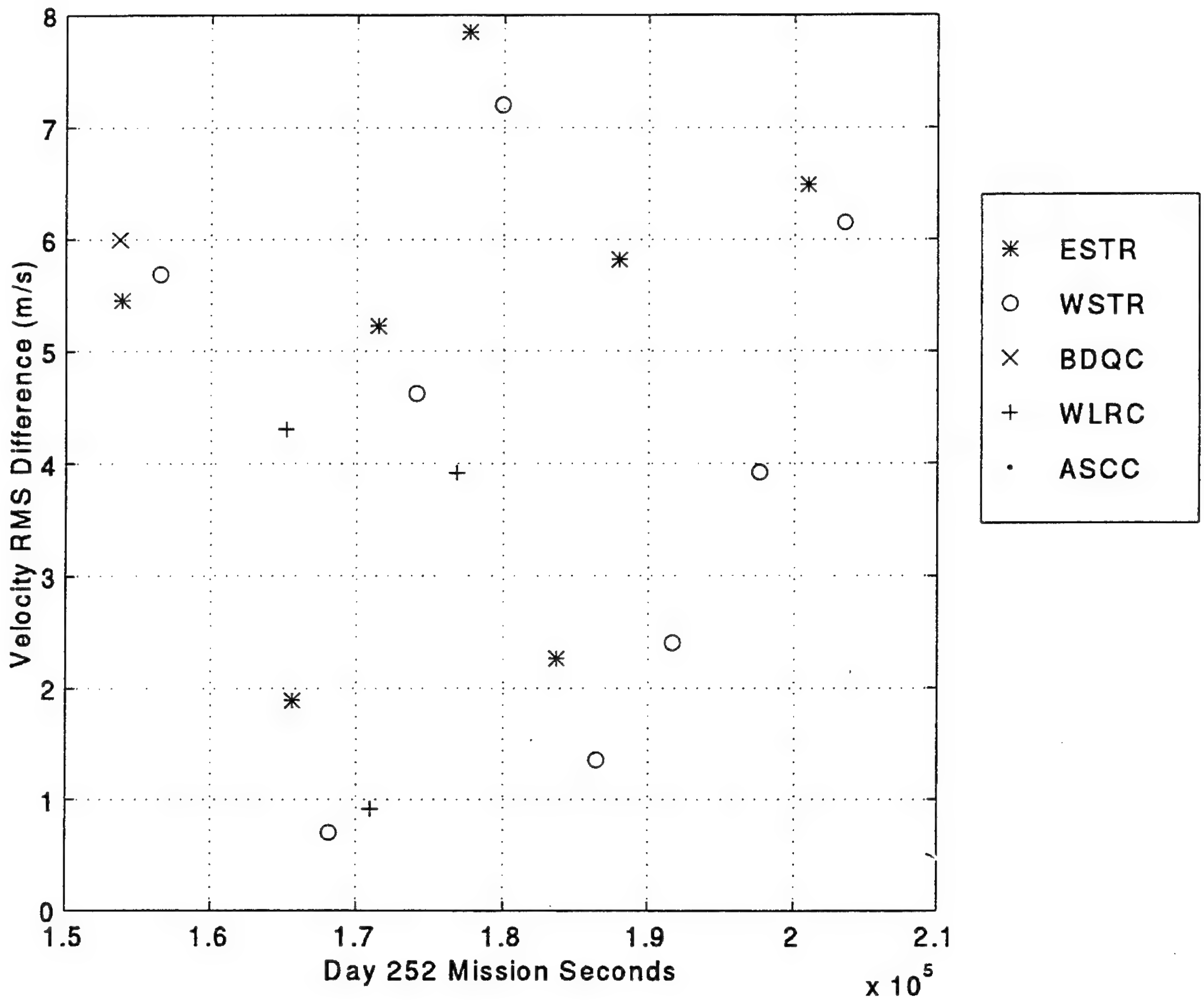
100
50
0
-50
-100
-150
-200
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
Position Vector Magnitude (Altitude) Difference (m)
ESTR
WSTR
BDQC
WLRC
ASCC



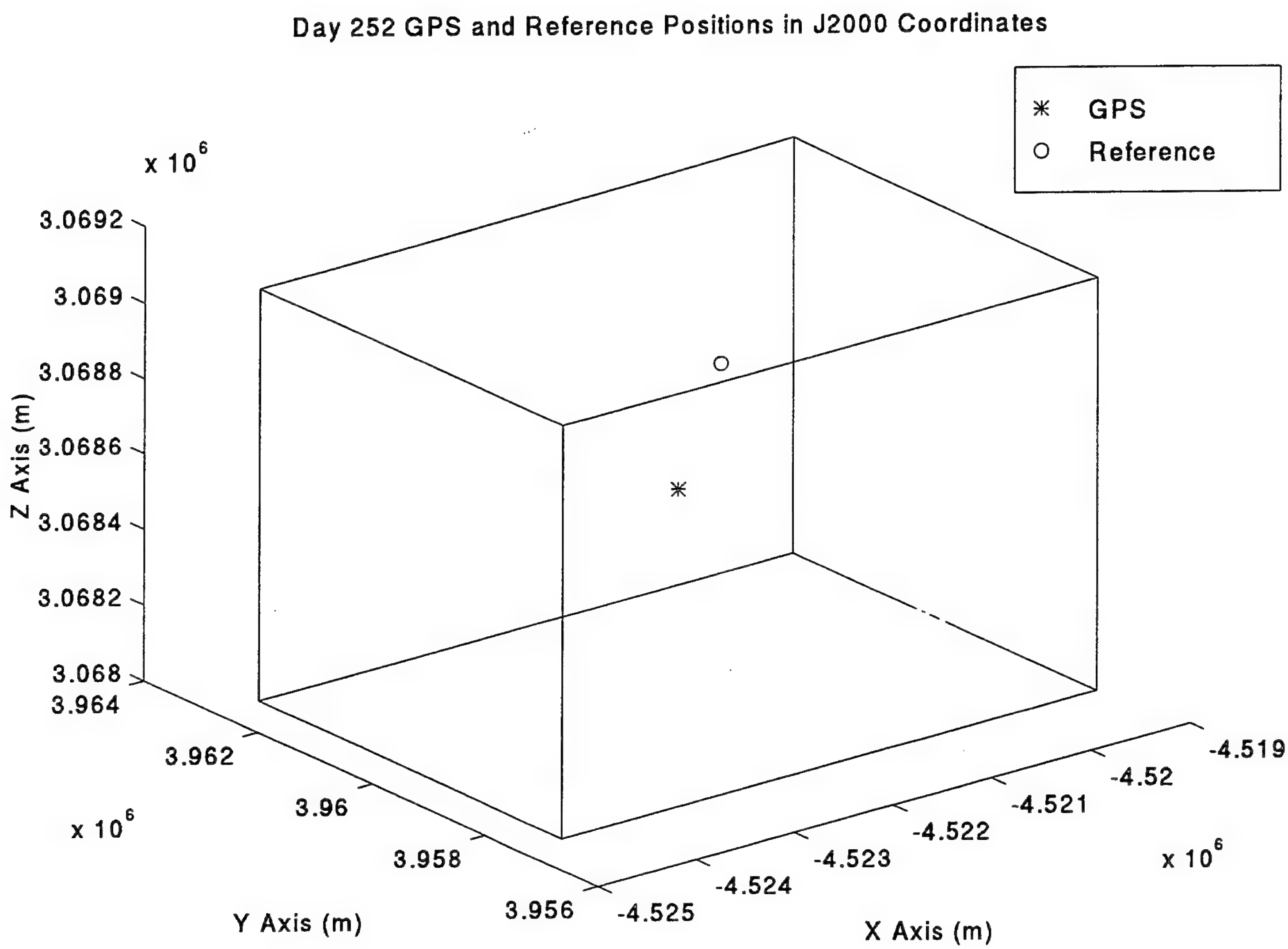
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
Velocity Vector Magnitude Difference (m/s)
ESTR
WSTR
BDQC
WLRC
ASCC

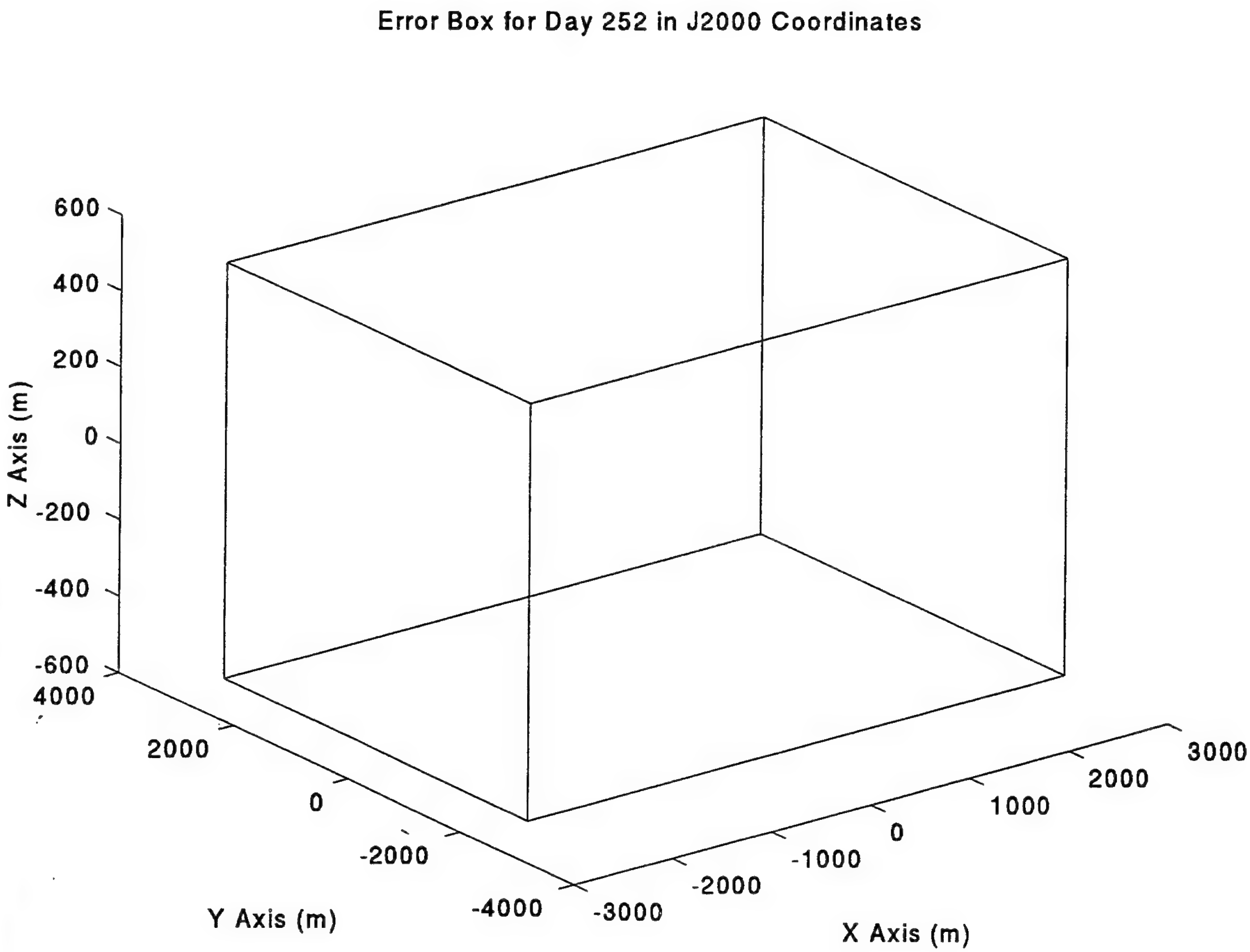


1750
1700
1650
1600
1550
1500
1450
1400
Position RMS Difference (m)
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
ESTR
WSTR
BDQC
WLRC
ASCC

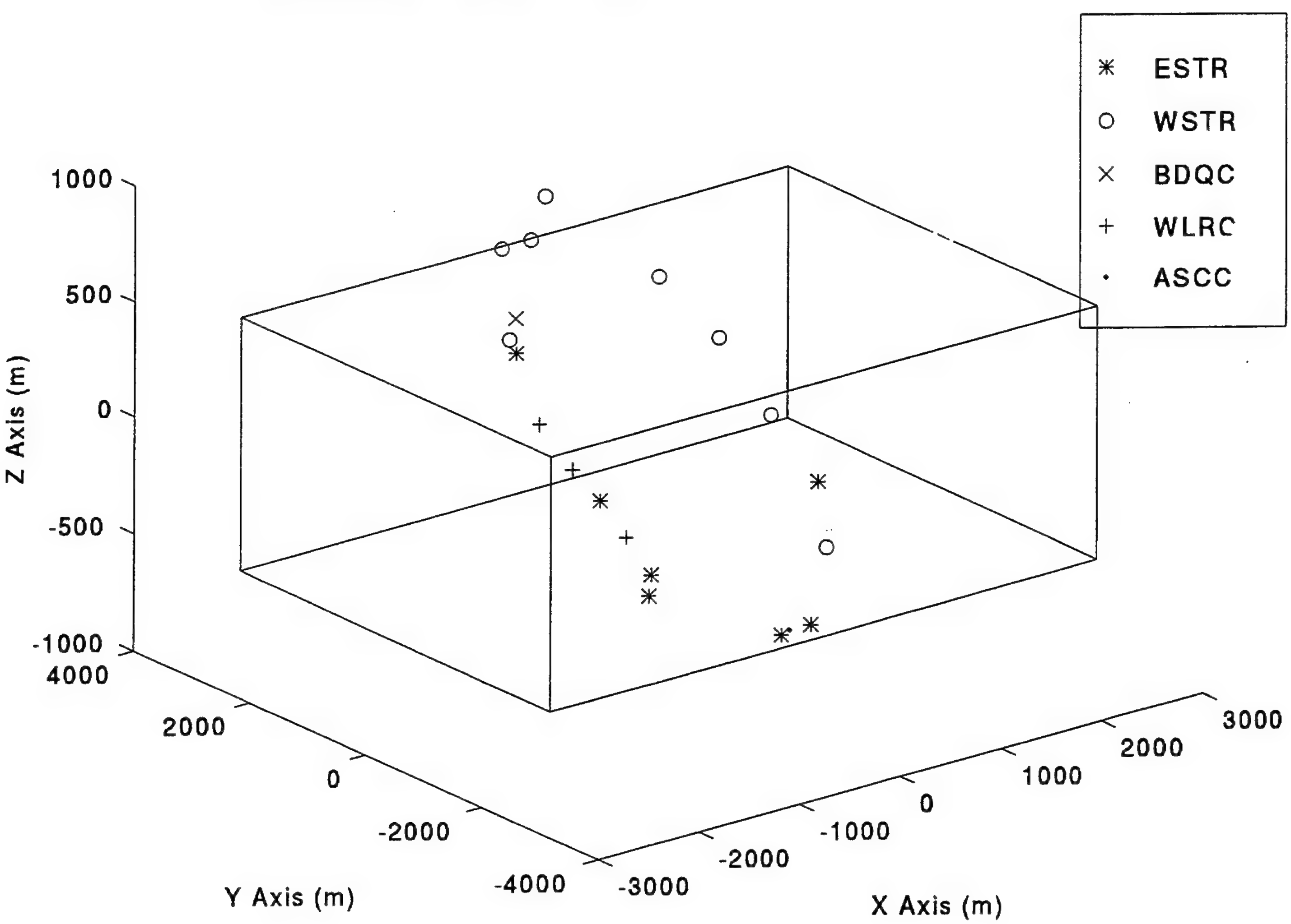


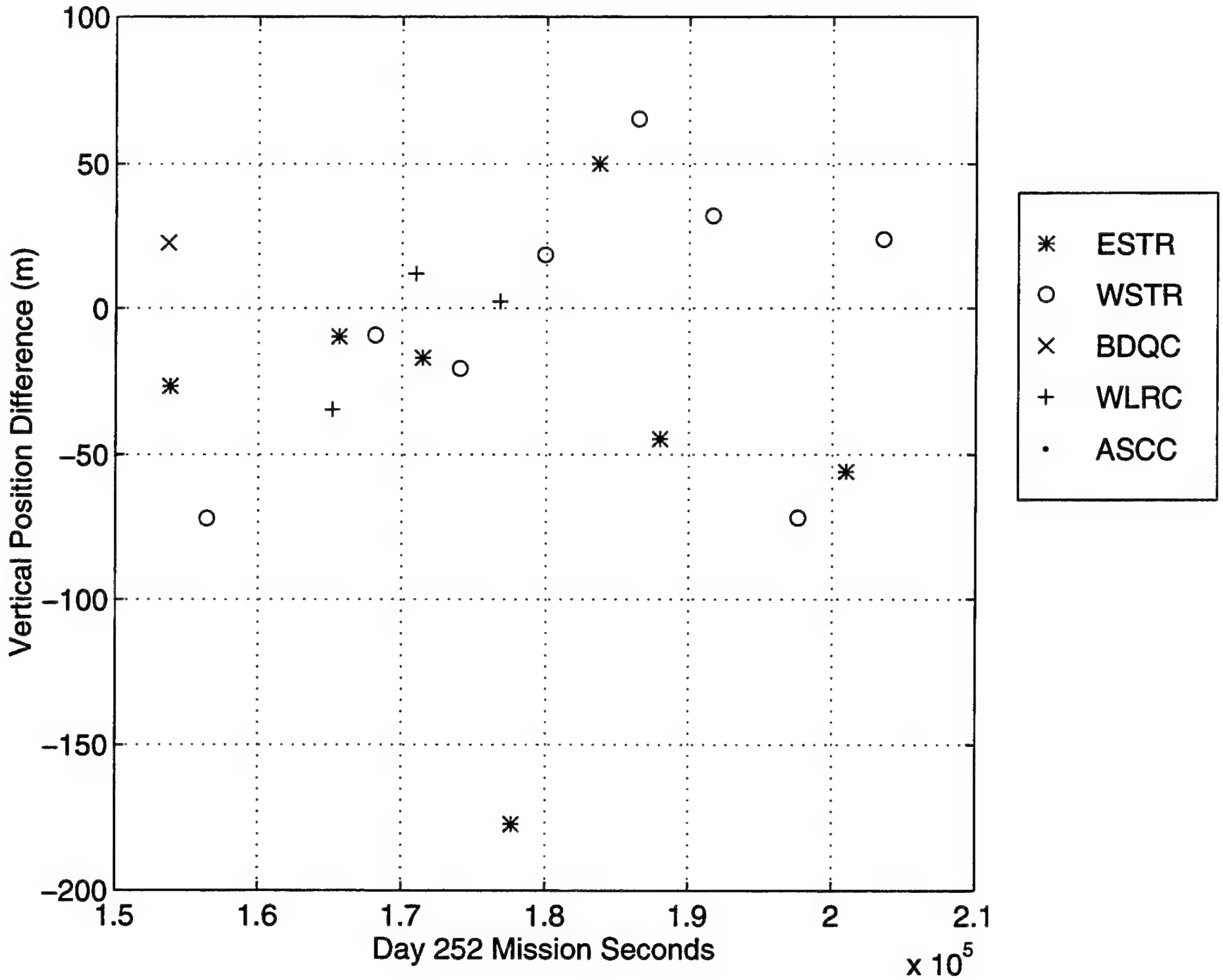
8
7
6
5
4
3
2
1
0
1.5
1.6
1.7
1.8
1.9
2
2.1
Velocity RMS Difference (m/s)
Day 252 Mission Seconds
x 10^5
ESTR
WSTR
BDQC
WLRC
ASCC


Day 252 GPS and Reference Positions in J2000 Coordinates
GPS
Reference
x 10^6
3.0692
3.069
3.0688
3.0686
3.0684
3.0682
3.068
Z Axis (m)
3.964
3.962
3.96
3.958
3.956
x 10^6
Y Axis (m)
-4.525
-4.524
-4.523
-4.522
-4.521
-4.52
-4.519
x 10^6
X Axis (m)

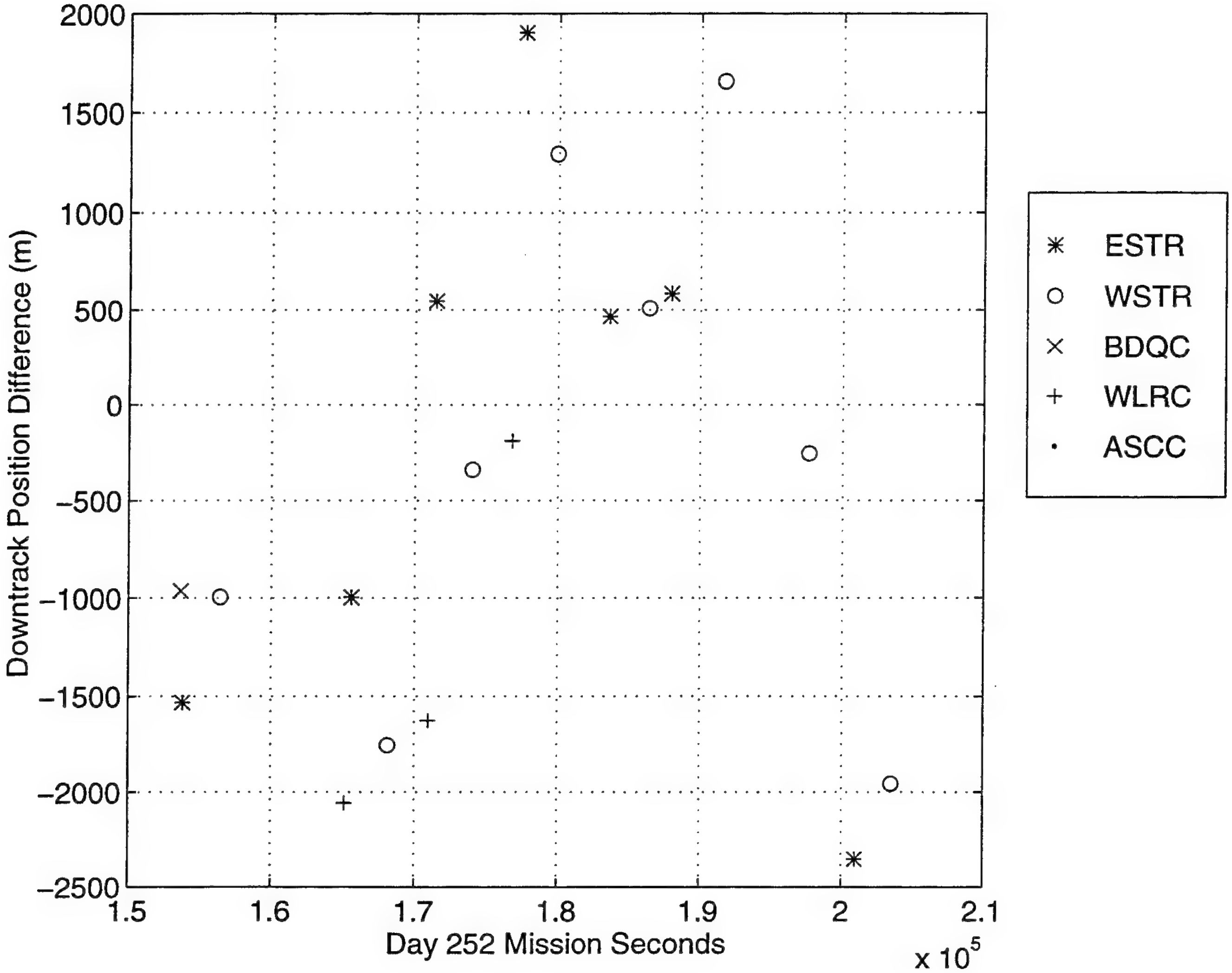

Error Box for Day 252 in J2000 Coordinates
600
400
200
0
-200
-400
-600
Z Axis (m)
4000
2000
0
-2000
-4000
Y Axis (m)
-3000
-2000
-1000
0
1000
2000
3000
X Axis (m)

Day 252 Error Box and Position Differences in J2000 Coordinates

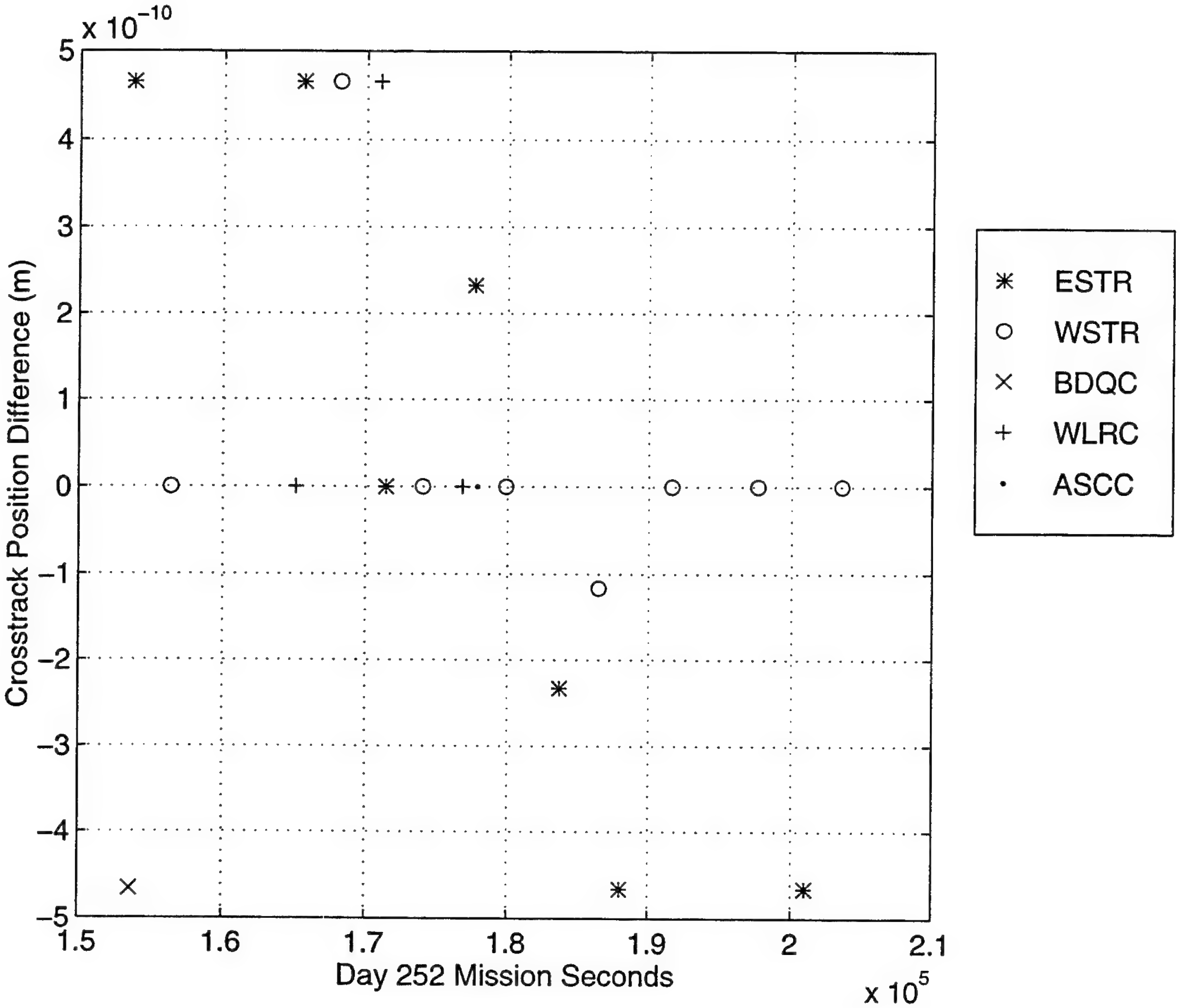


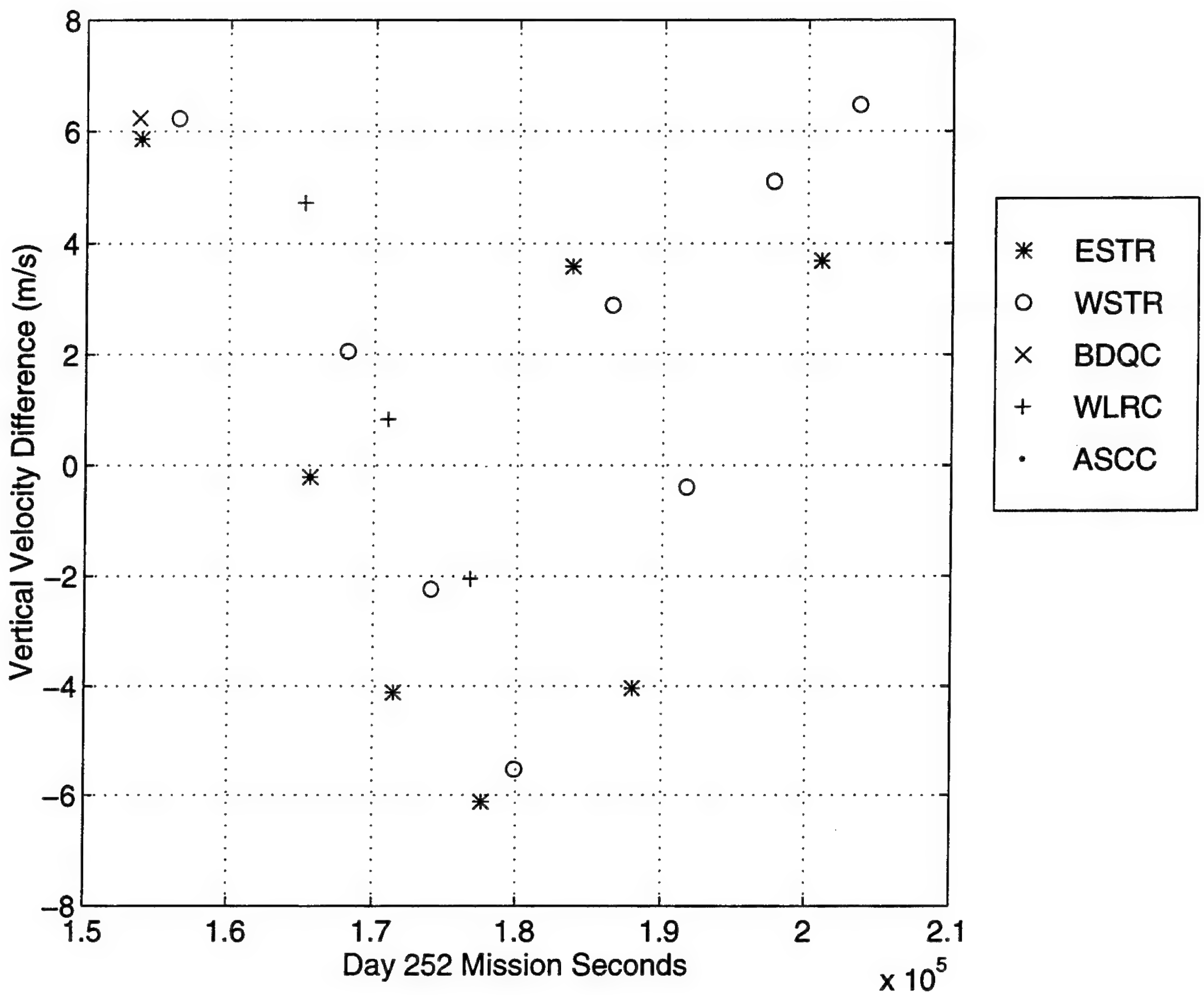


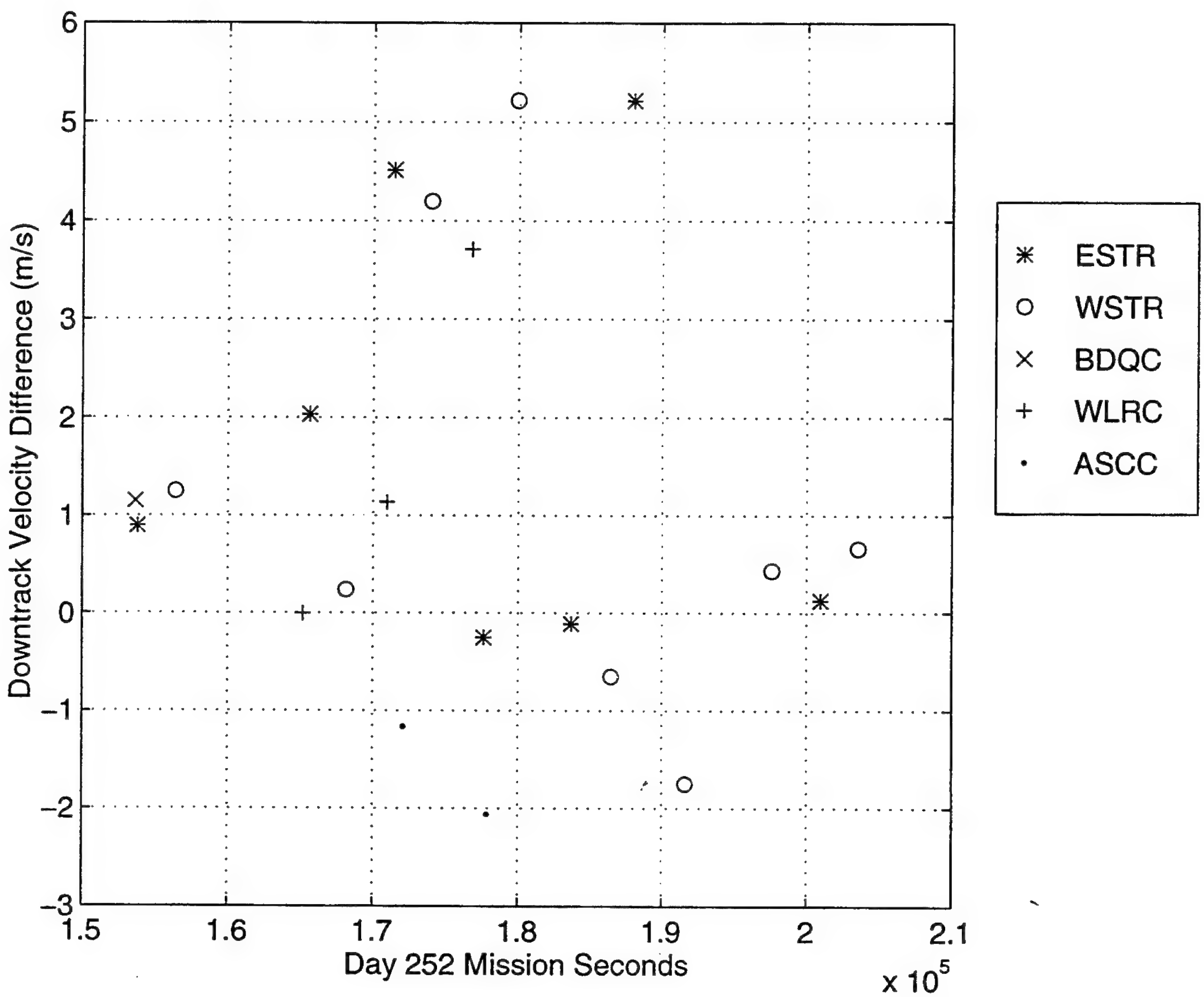
100
50
0
−50
−100
−150
−200
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
Vertical Position Difference (m)
ESTR
WSTR
BDQC
WLRC
ASCC



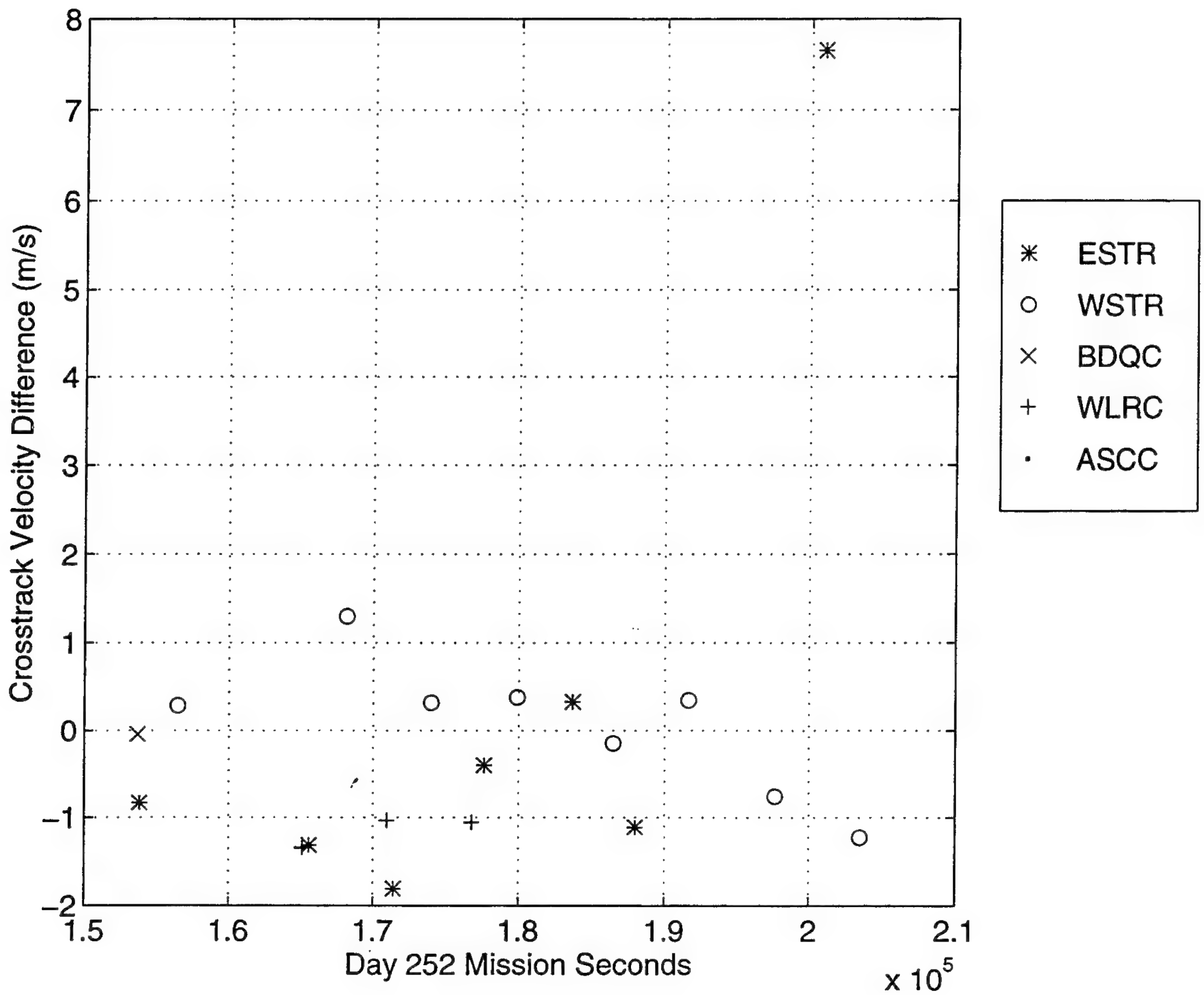
Downtrack Position Difference (m)
Day 252 Mission Seconds
x 10^5
2000
1500
1000
500
0
−500
−1000
−1500
−2000
−2500
1.5
1.6
1.7
1.8
1.9
2
2.1
ESTR
WSTR
BDQC
WLRC
ASCC


x 10^-10
5
4
3
2
1
0
−1
−2
−3
−4
−5
Crosstrack Position Difference (m)
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
ESTR
WSTR
BDQC
WLRC
ASCC


8
6
4
2
0
−2
−4
−6
−8
1.5
1.6
1.7
1.8
1.9
2
2.1
Vertical Velocity Difference (m/s)
Day 252 Mission Seconds
x 10^5
ESTR
WSTR
BDQC
WLRC
ASCC

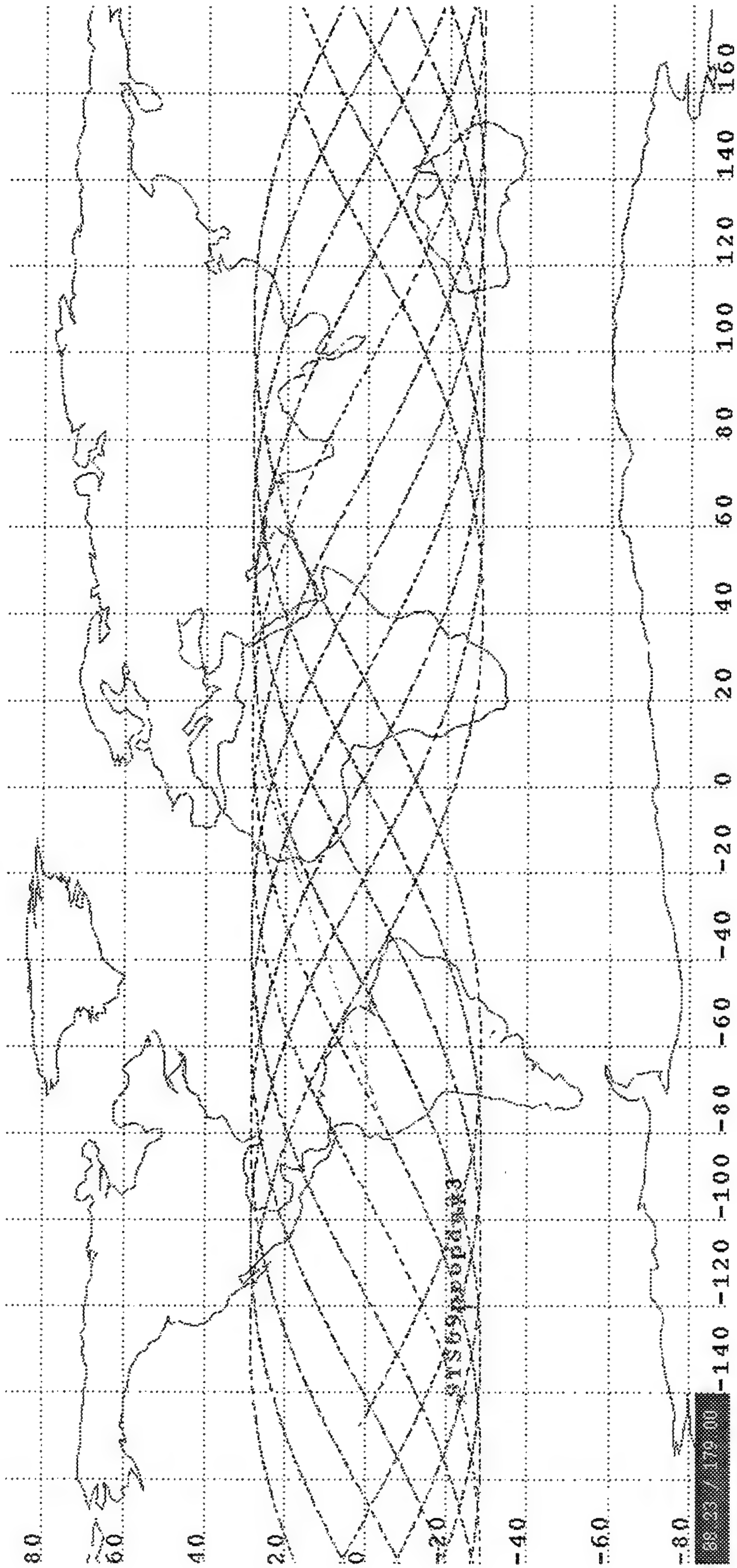


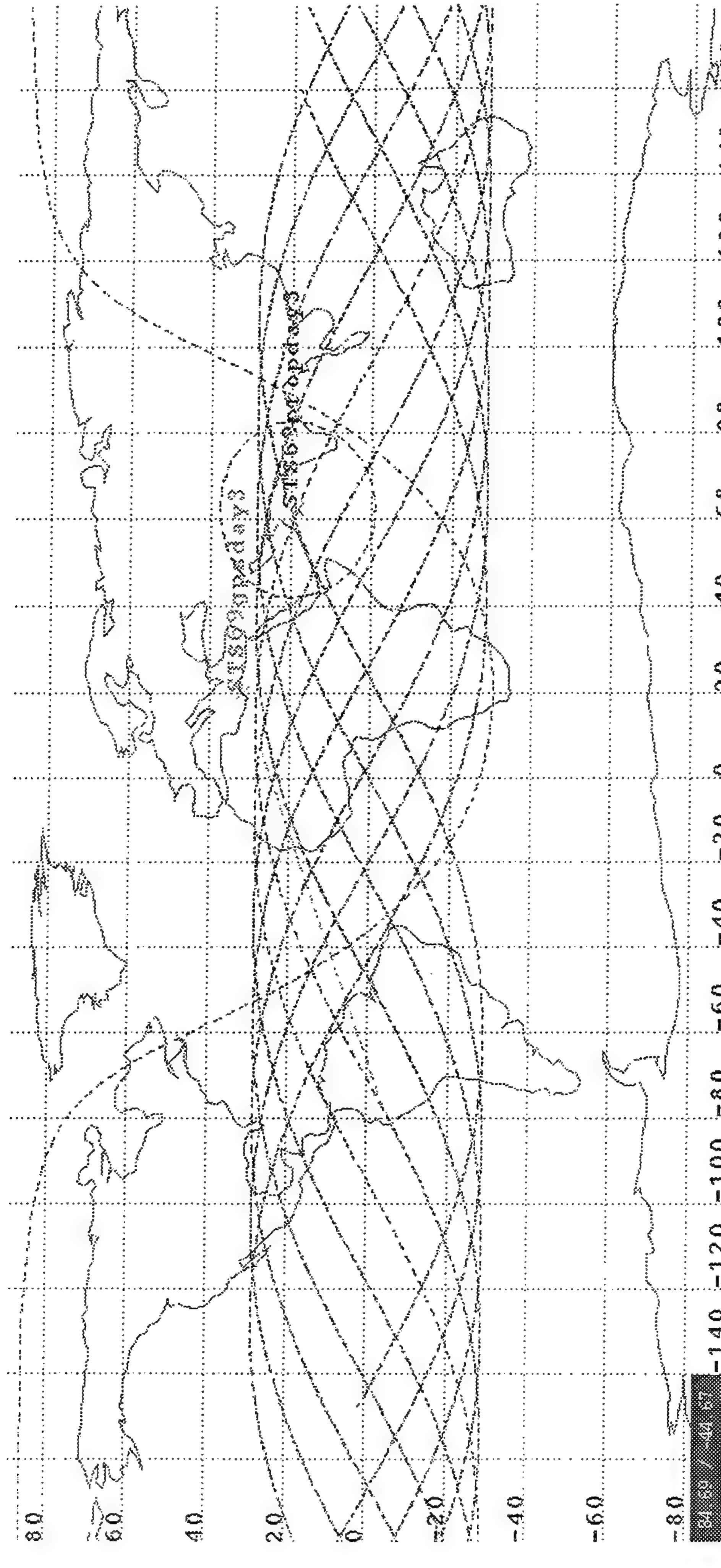
6
5
4
3
2
1
0
−1
−2
−3
Downtrack Velocity Difference (m/s)
1.5
1.6
1.7
1.8
1.9
2
2.1
Day 252 Mission Seconds
x 10^5
ESTR
WSTR
BDQC
WLRC
ASCC



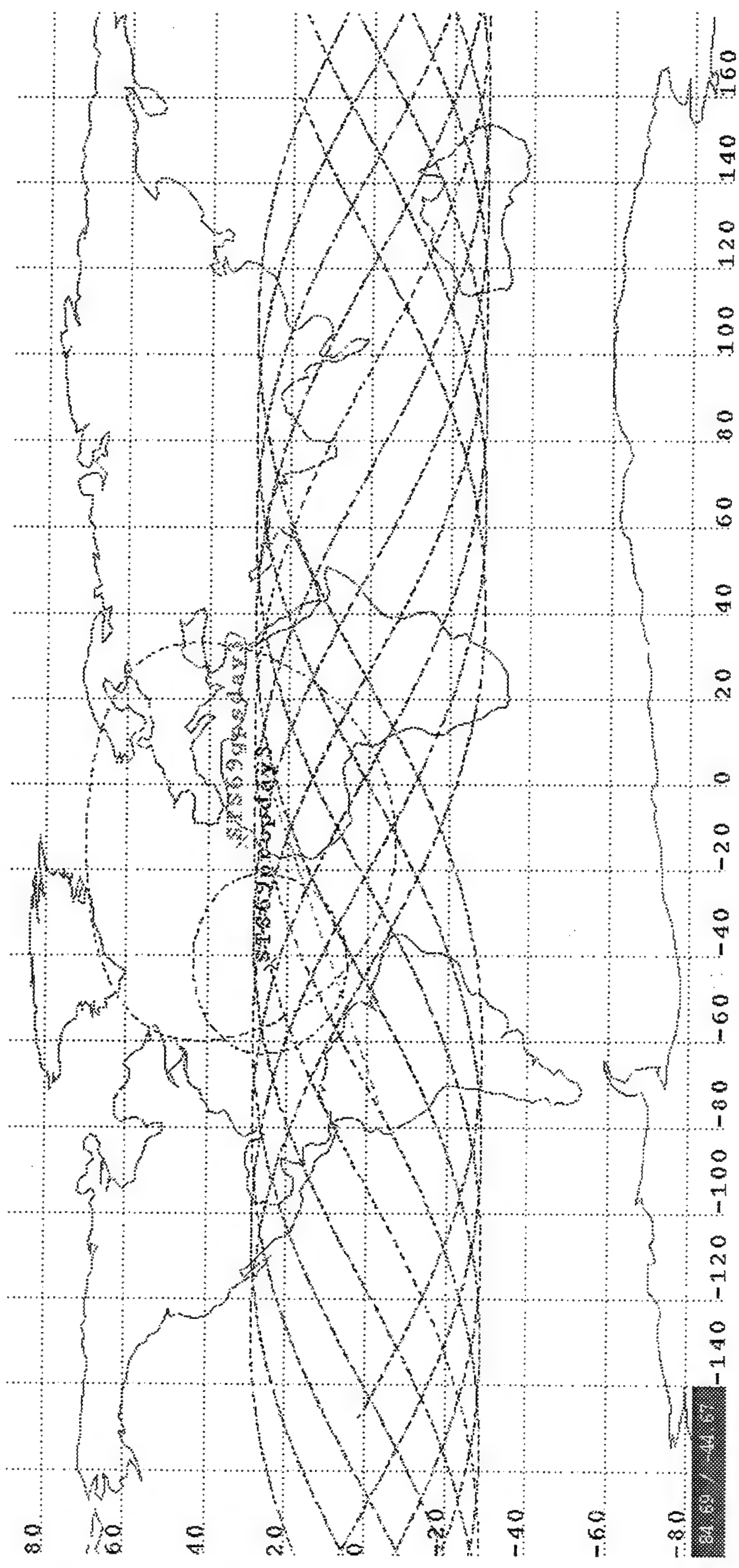
Crosstrack Velocity Difference (m/s)
Day 252 Mission Seconds
x 10^5
8
7
6
5
4
3
2
1
0
−1
−2
1.5
1.6
1.7
1.8
1.9
2
2.1
ESTR
WSTR
BDQC
WLRC
ASCC

APPENDIX N. DAY 253 STK PLOTS

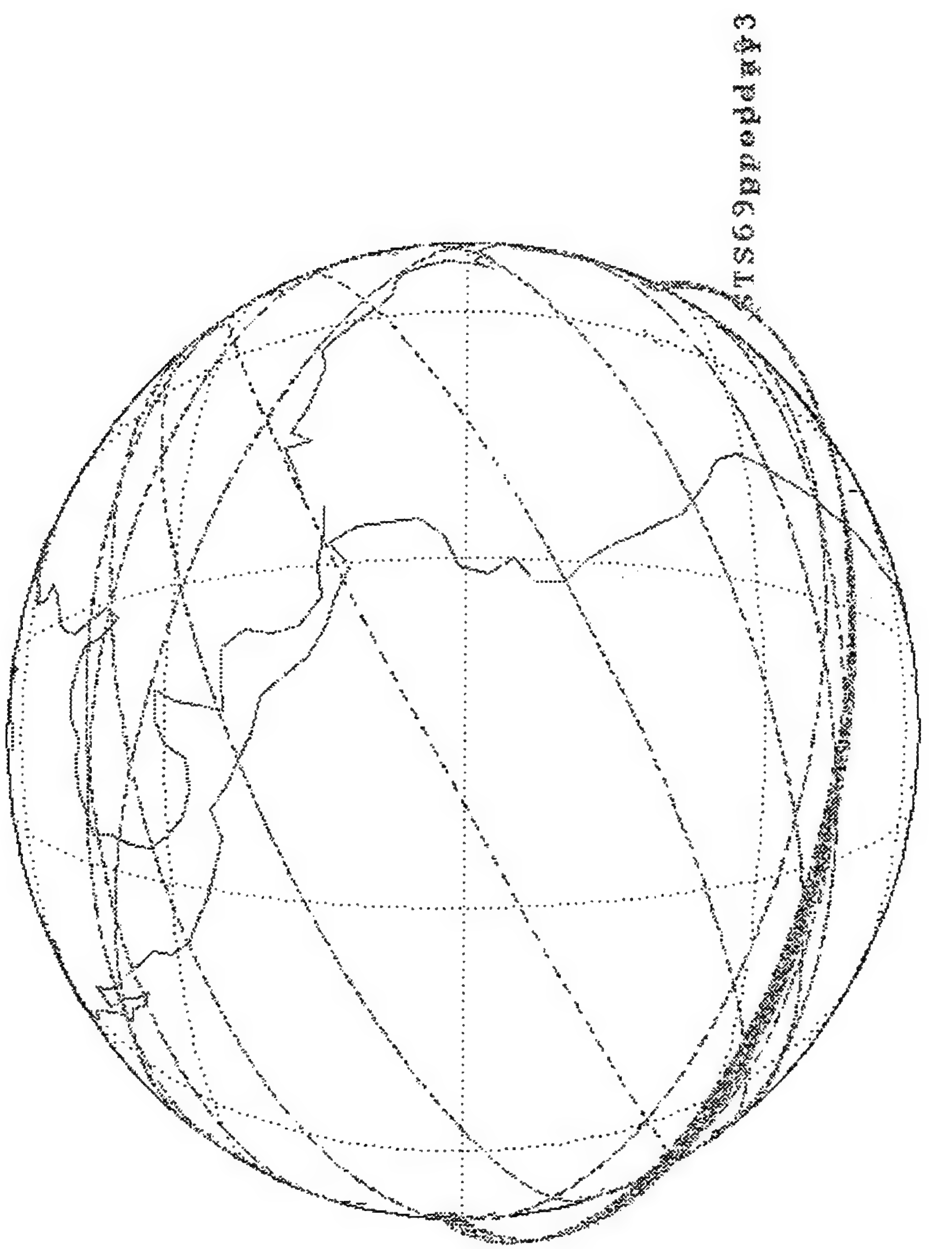

80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

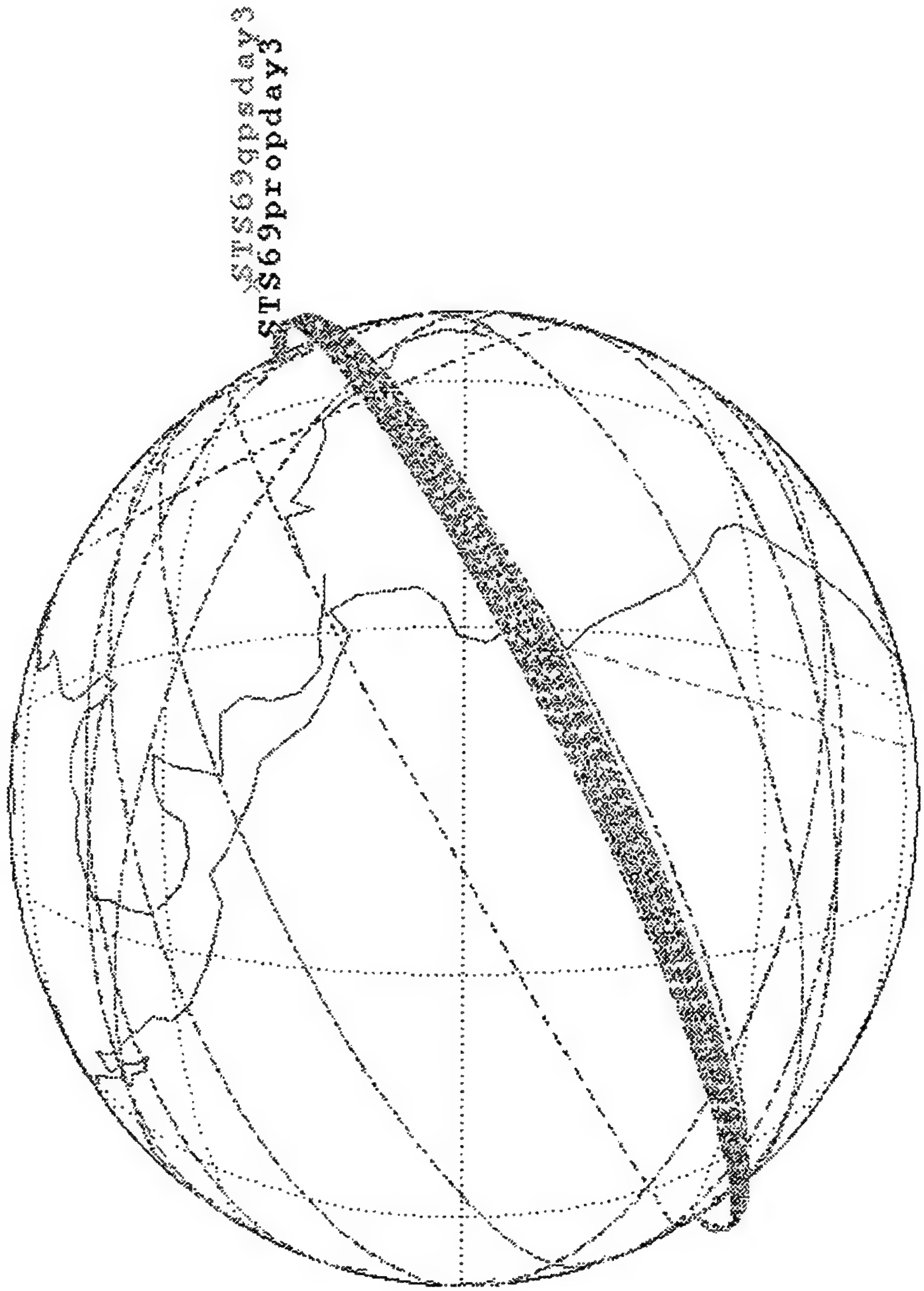


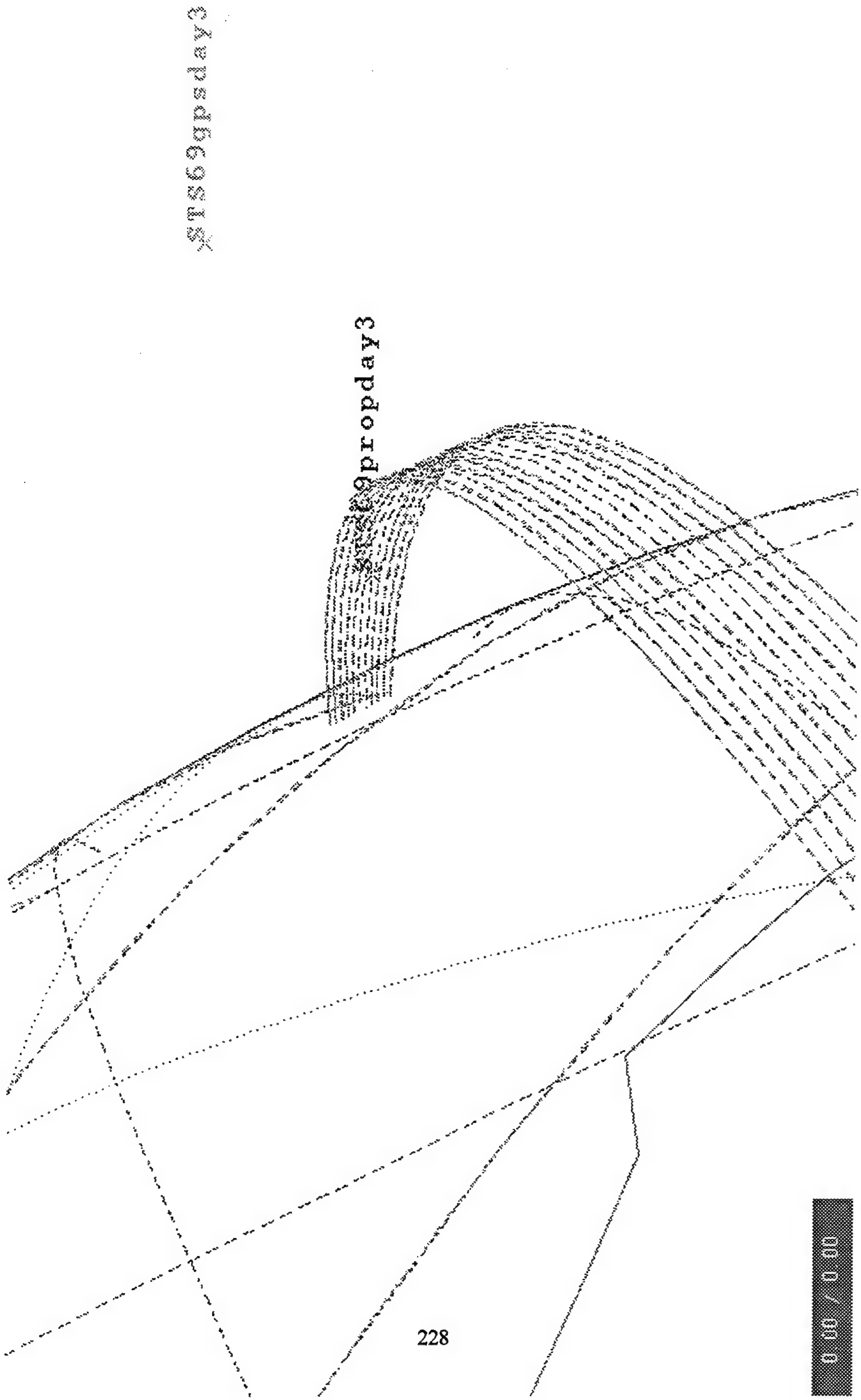
80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160



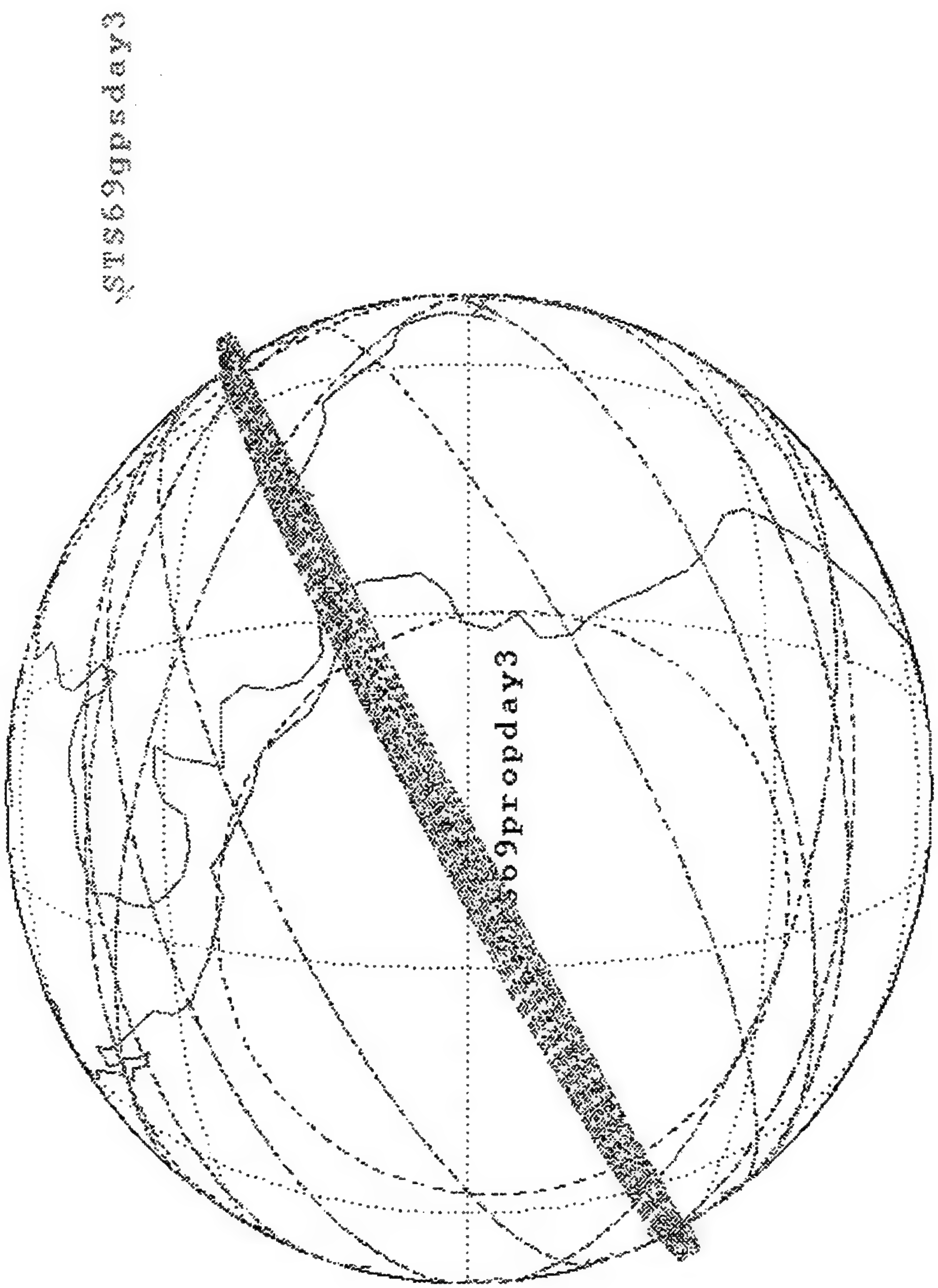
80
60
40
20
0
-20
-40
-60
-80
-140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160



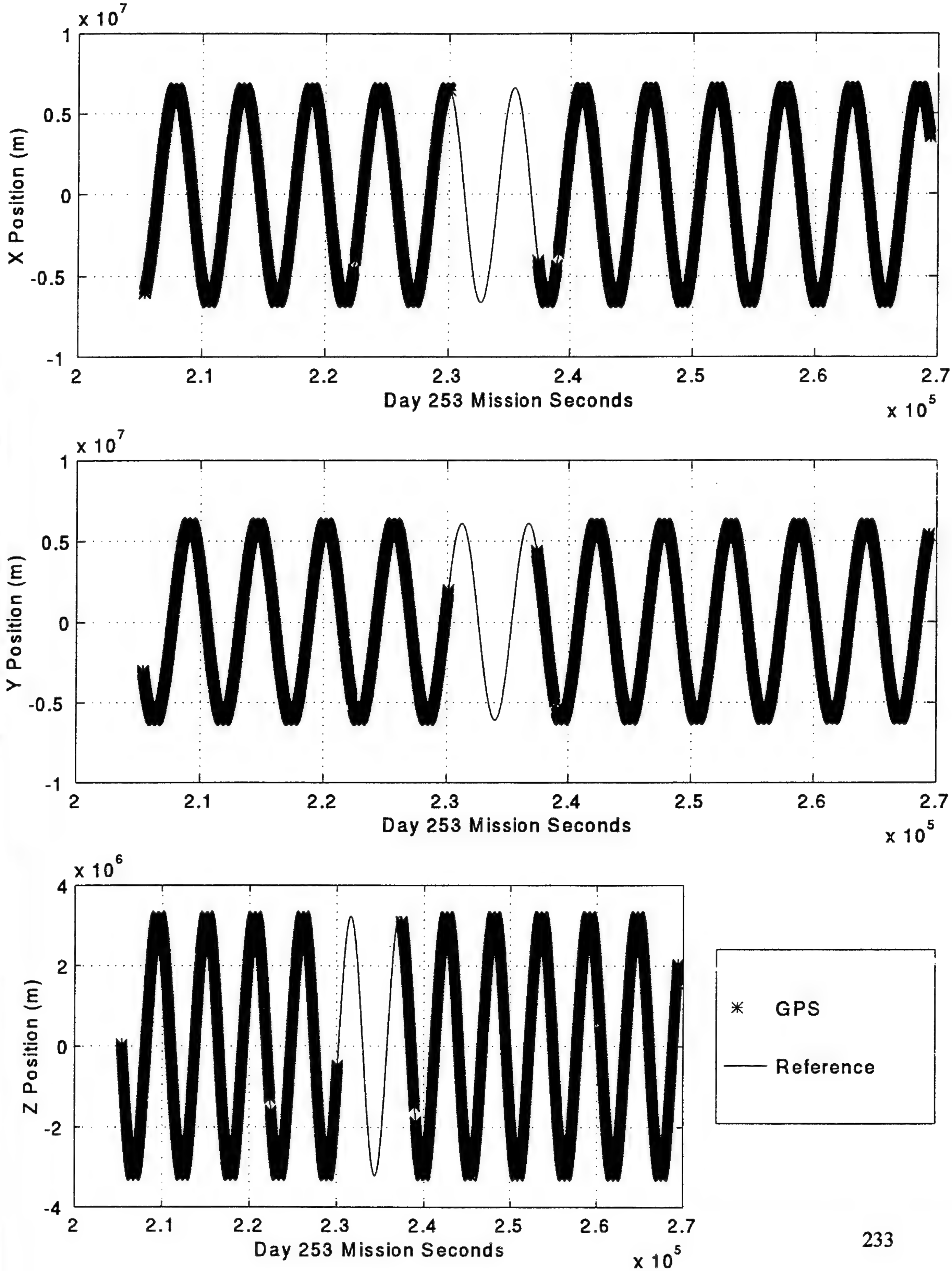

STS69gpsday3
STS69propday3

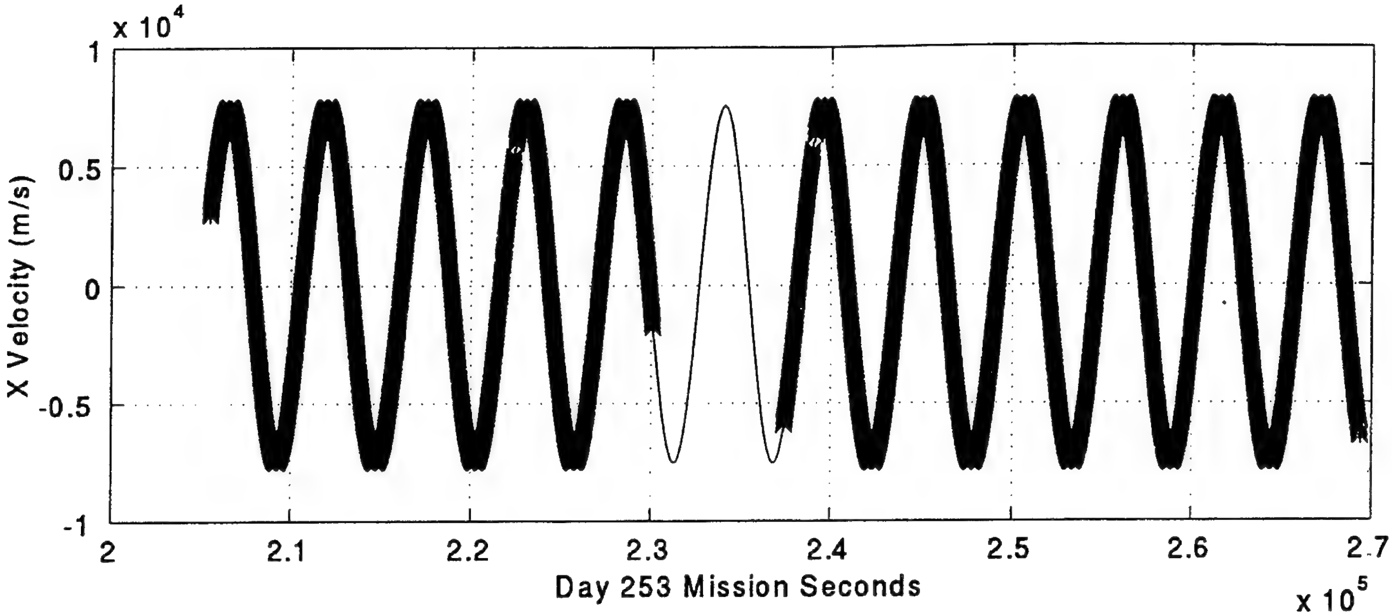


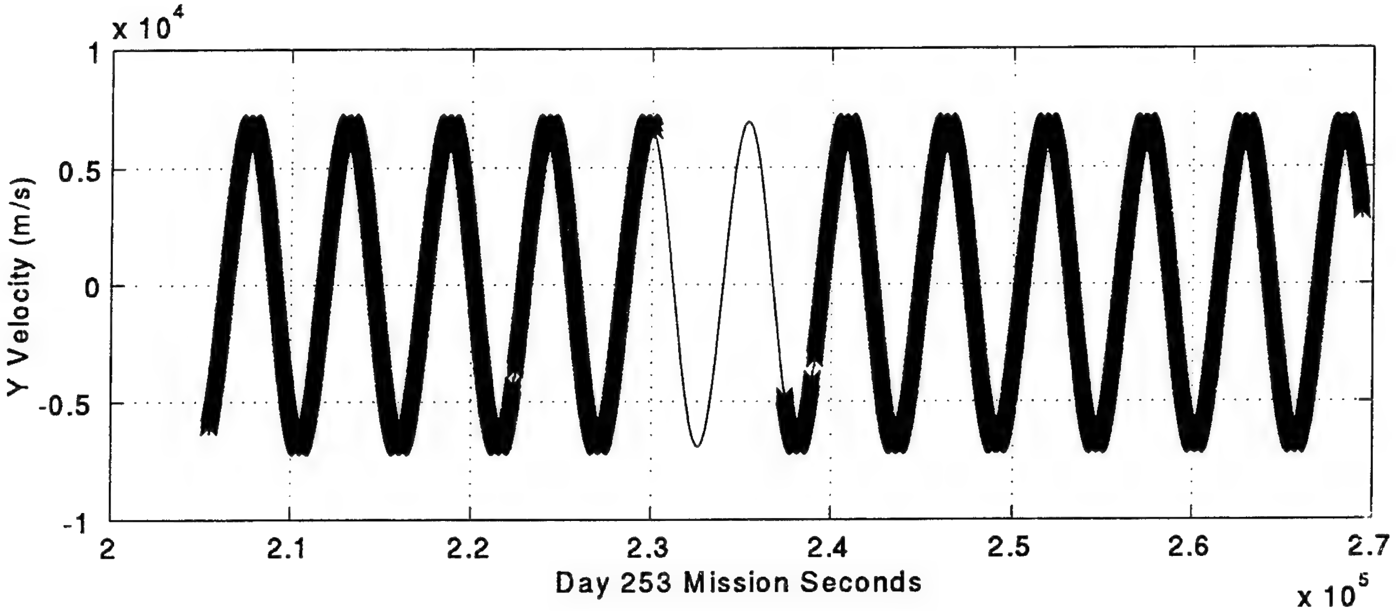
$TS69gpsday3
9propday3
0.00 / 0.00

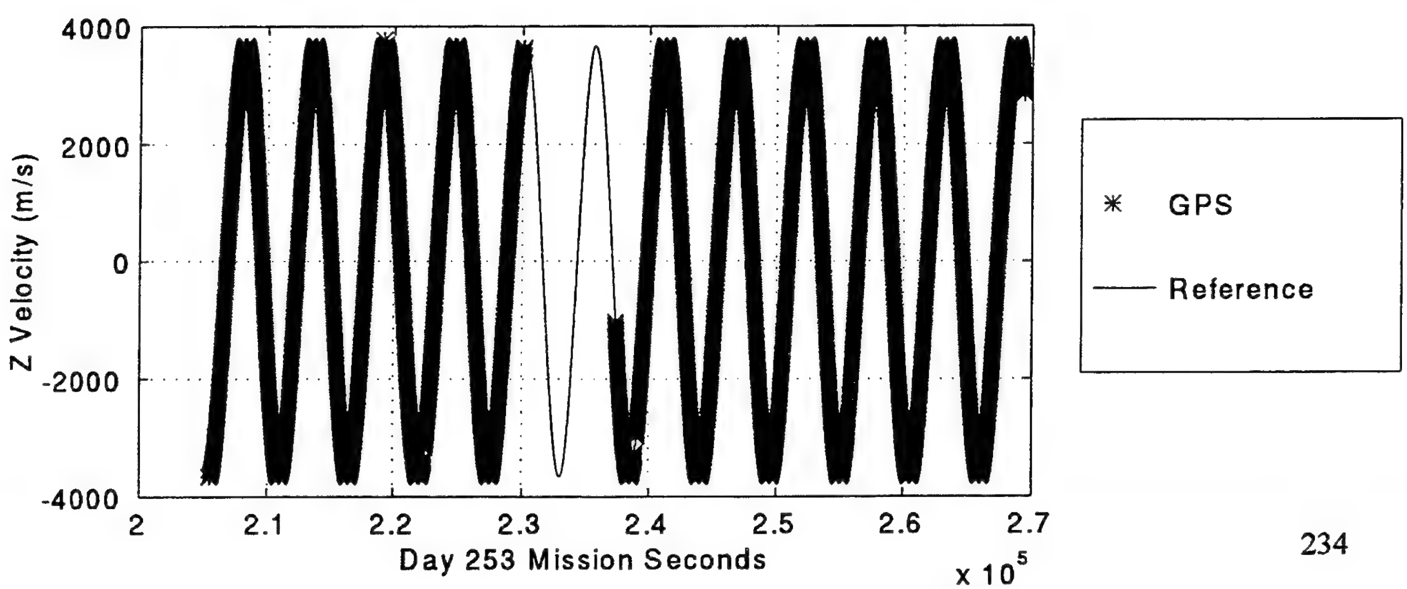

STS69gpsday3
S69propday3

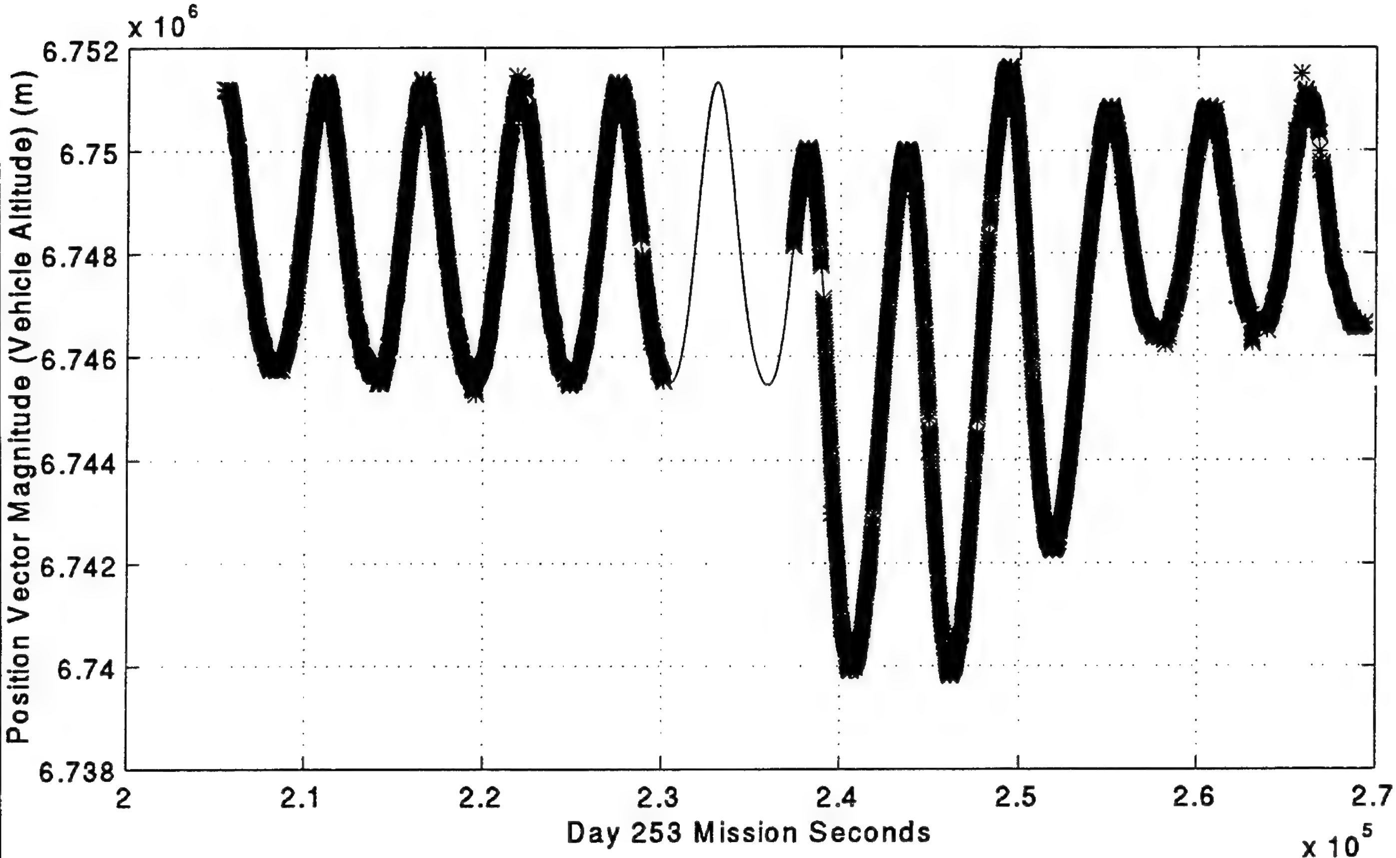
APPENDIX O. DAY 253 MATLAB PLOTS

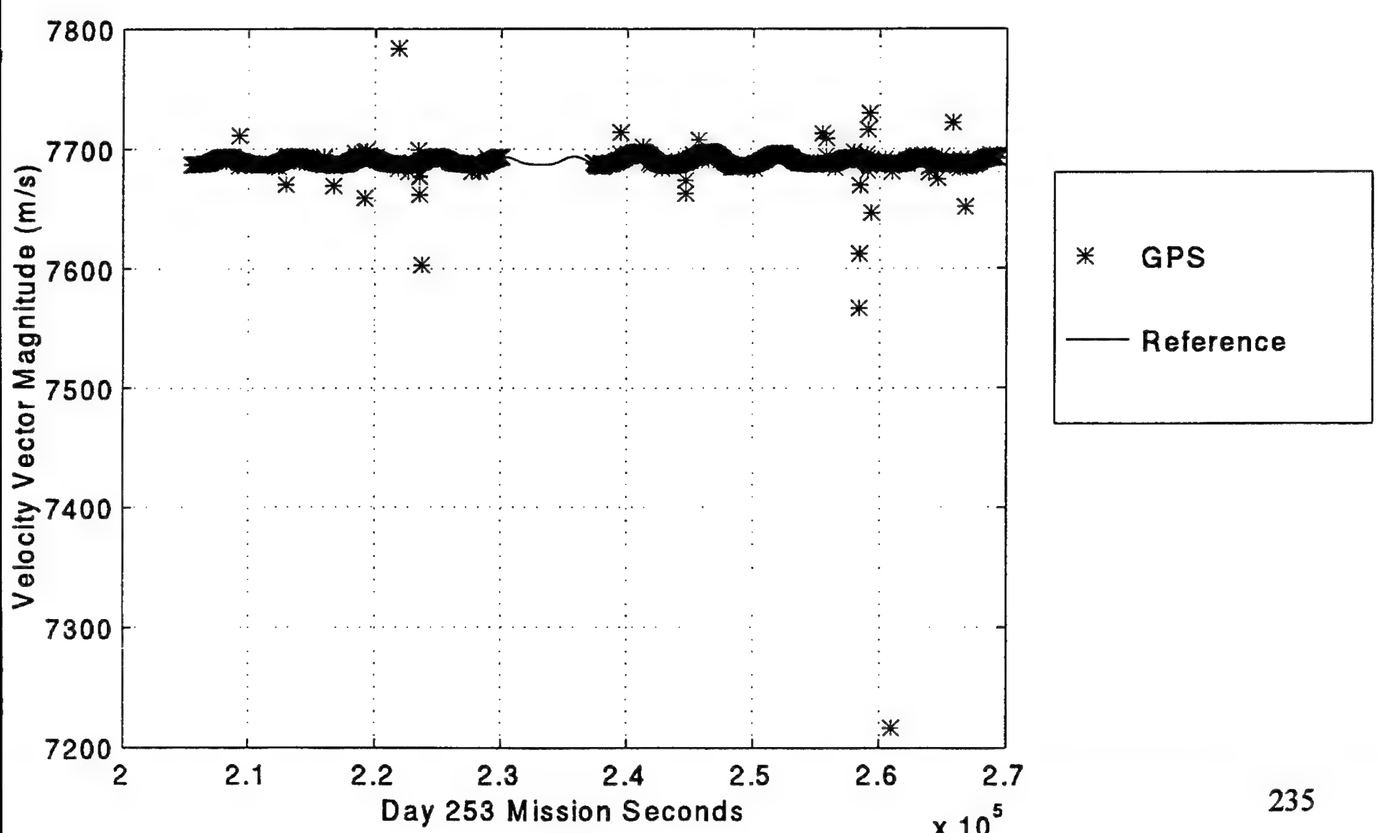

x 10^7
X Position (m)
Day 253 Mission Seconds
x 10^5
x 10^7
Y Position (m)
Day 253 Mission Seconds
x 10^5
x 10^6
Z Position (m)
Day 253 Mission Seconds
x 10^5
GPS
Reference


x 10^4
1
0.5
0
-0.5
-1
X Velocity (m/s)
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
Day 253 Mission Seconds
x 10^5

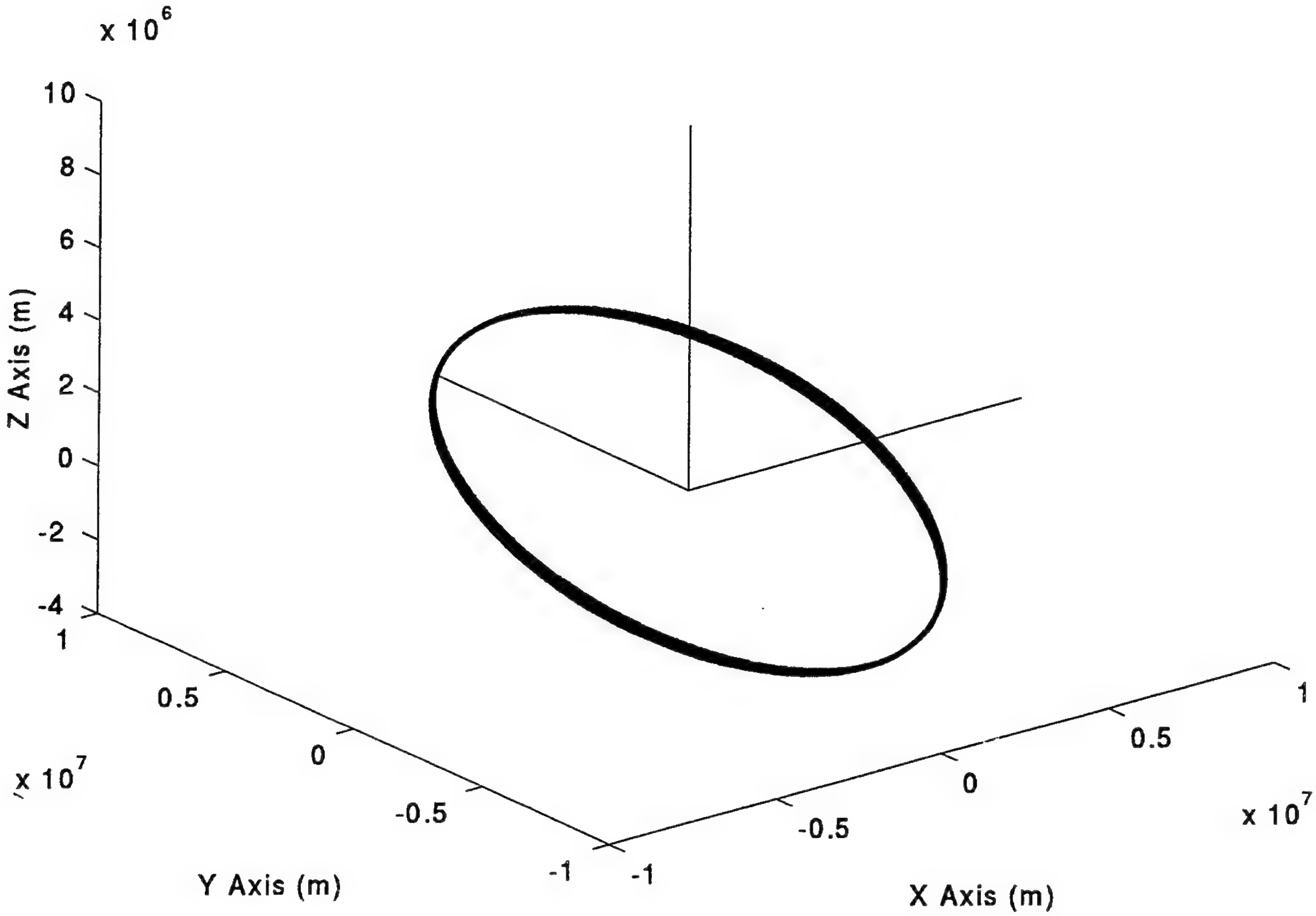

x 10^4
1
0.5
0
-0.5
-1
Y Velocity (m/s)
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
Day 253 Mission Seconds
x 10^5


4000
2000
0
-2000
-4000
Z Velocity (m/s)
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
Day 253 Mission Seconds
x 10^5
GPS
Reference

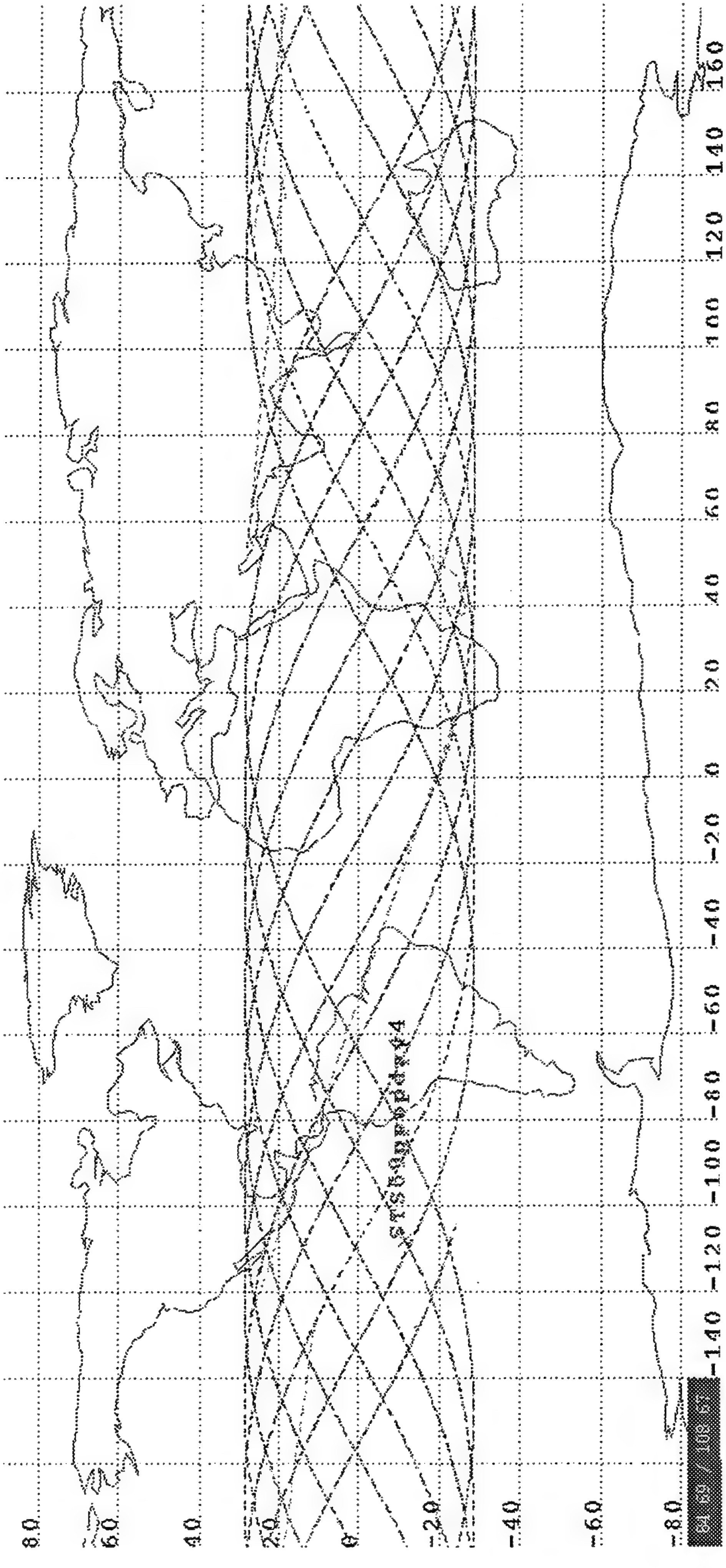

x 10^6
6.752
6.75
6.748
6.746
6.744
6.742
6.74
6.738
Position Vector Magnitude (Vehicle Altitude) (m)
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
Day 253 Mission Seconds
x 10^5

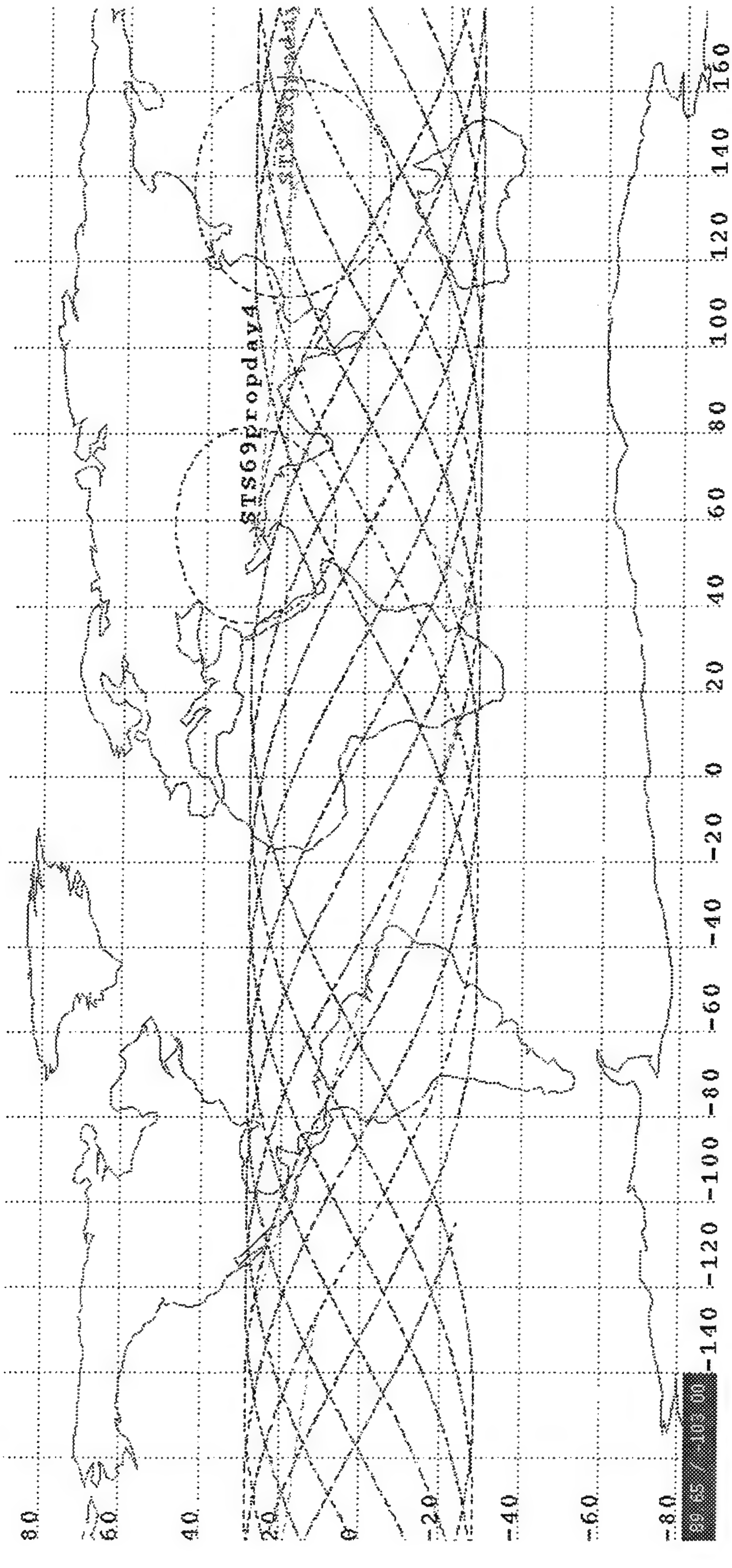

7800
7700
7600
7500
7400
7300
7200
Velocity Vector Magnitude (m/s)
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
Day 253 Mission Seconds
x 10^5
GPS
Reference

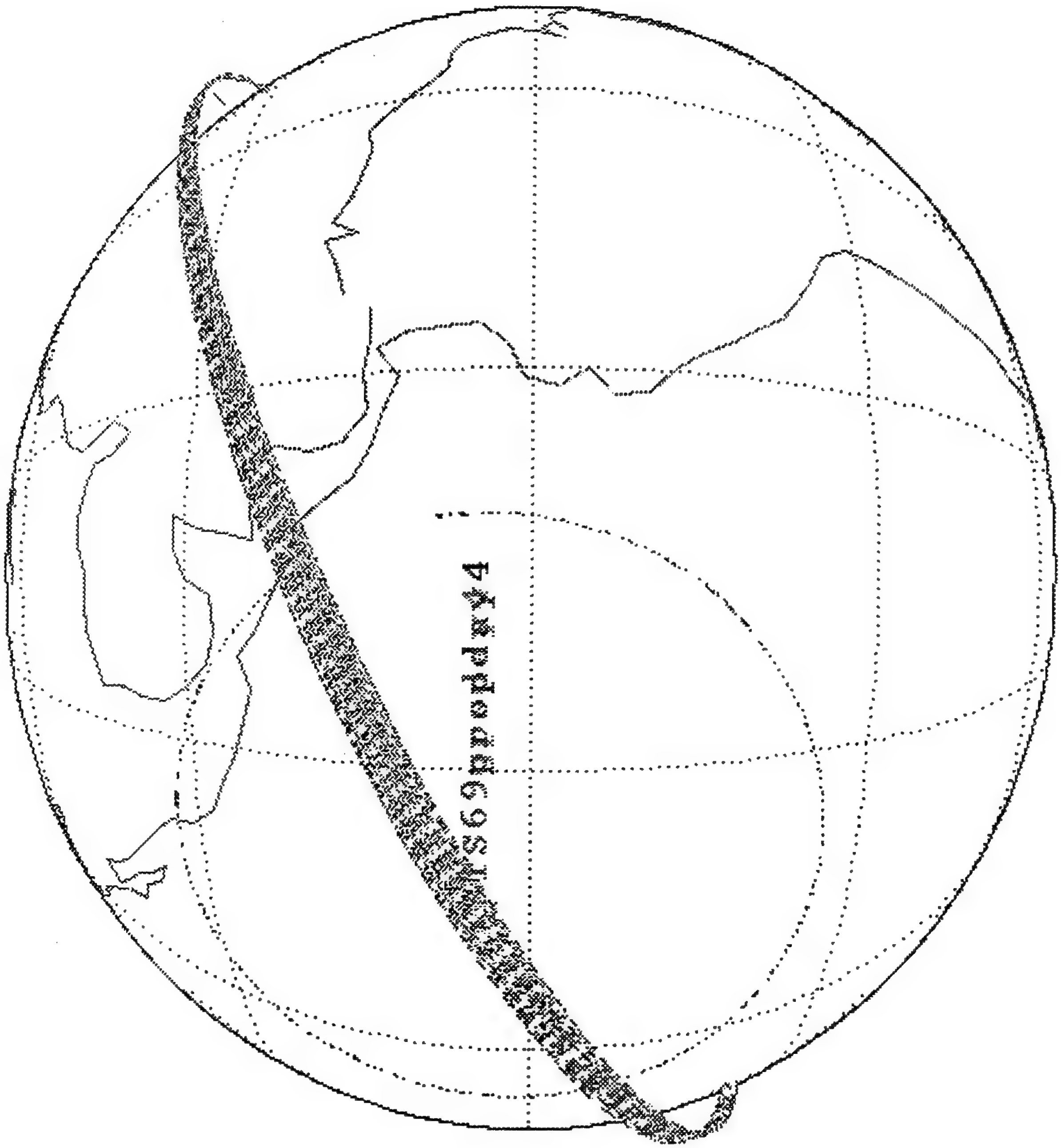
GPS Orbit for Day 253 in J2000 Coordinates



APPENDIX P. DAY 254 STK PLOTS

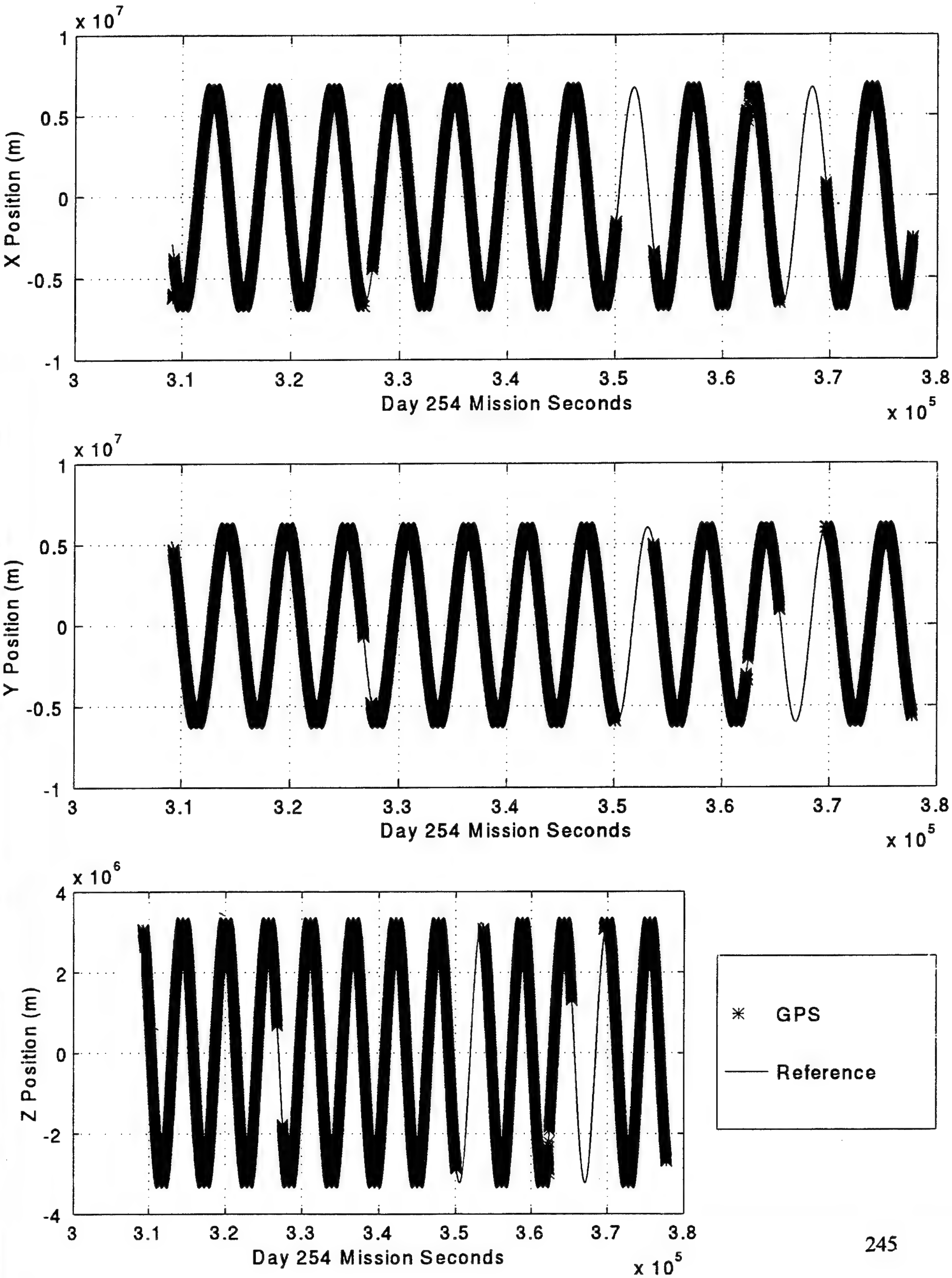

80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

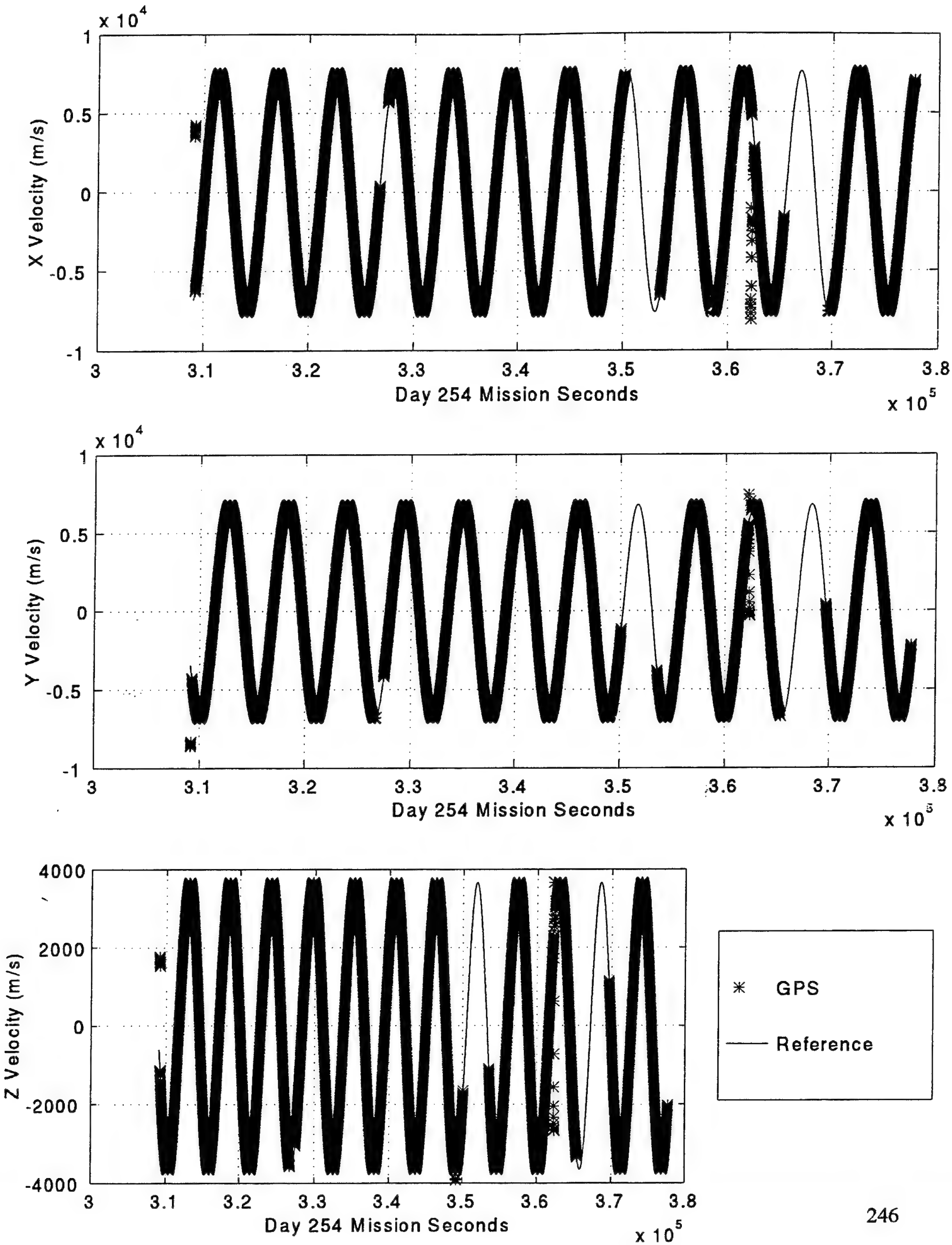

STS69propday4
80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

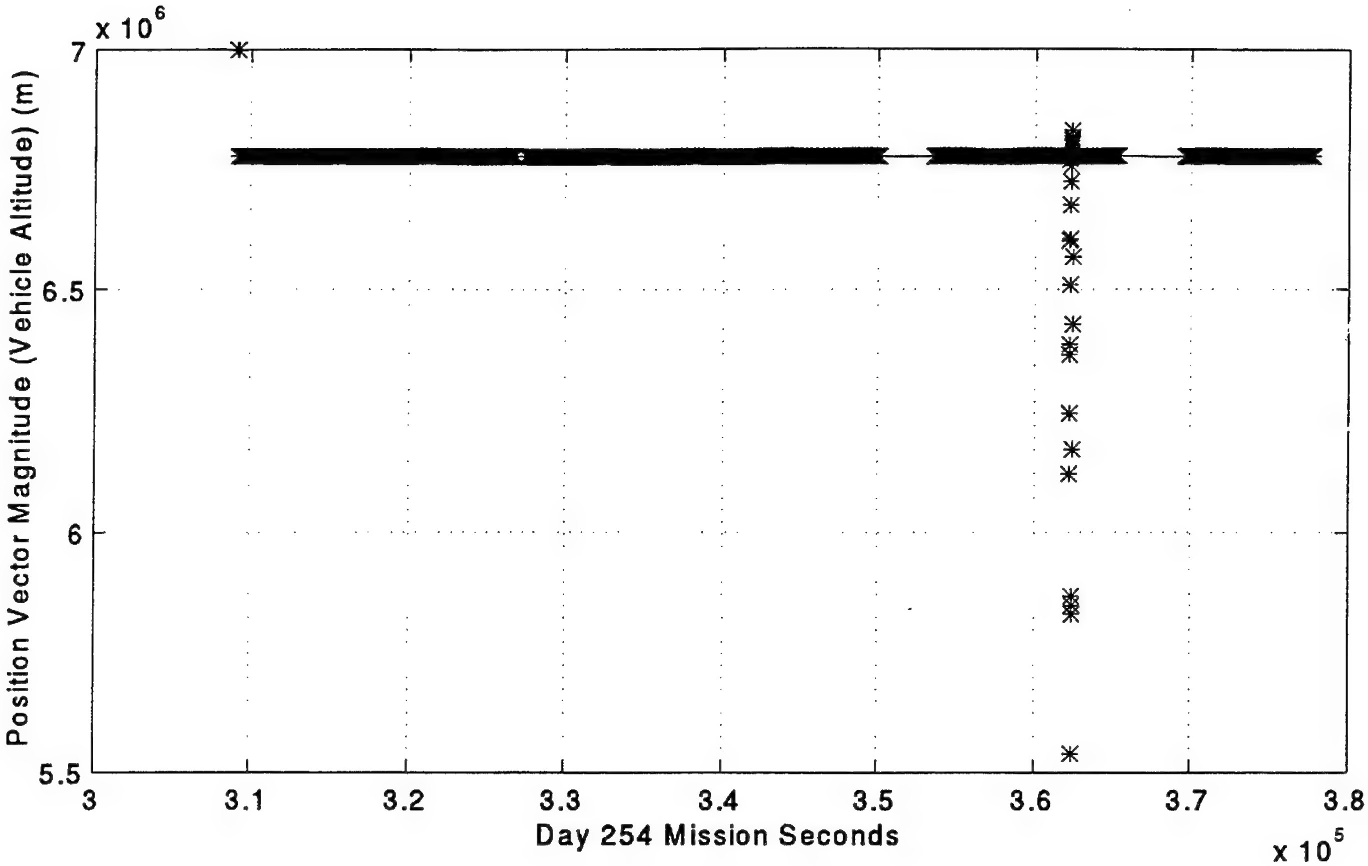


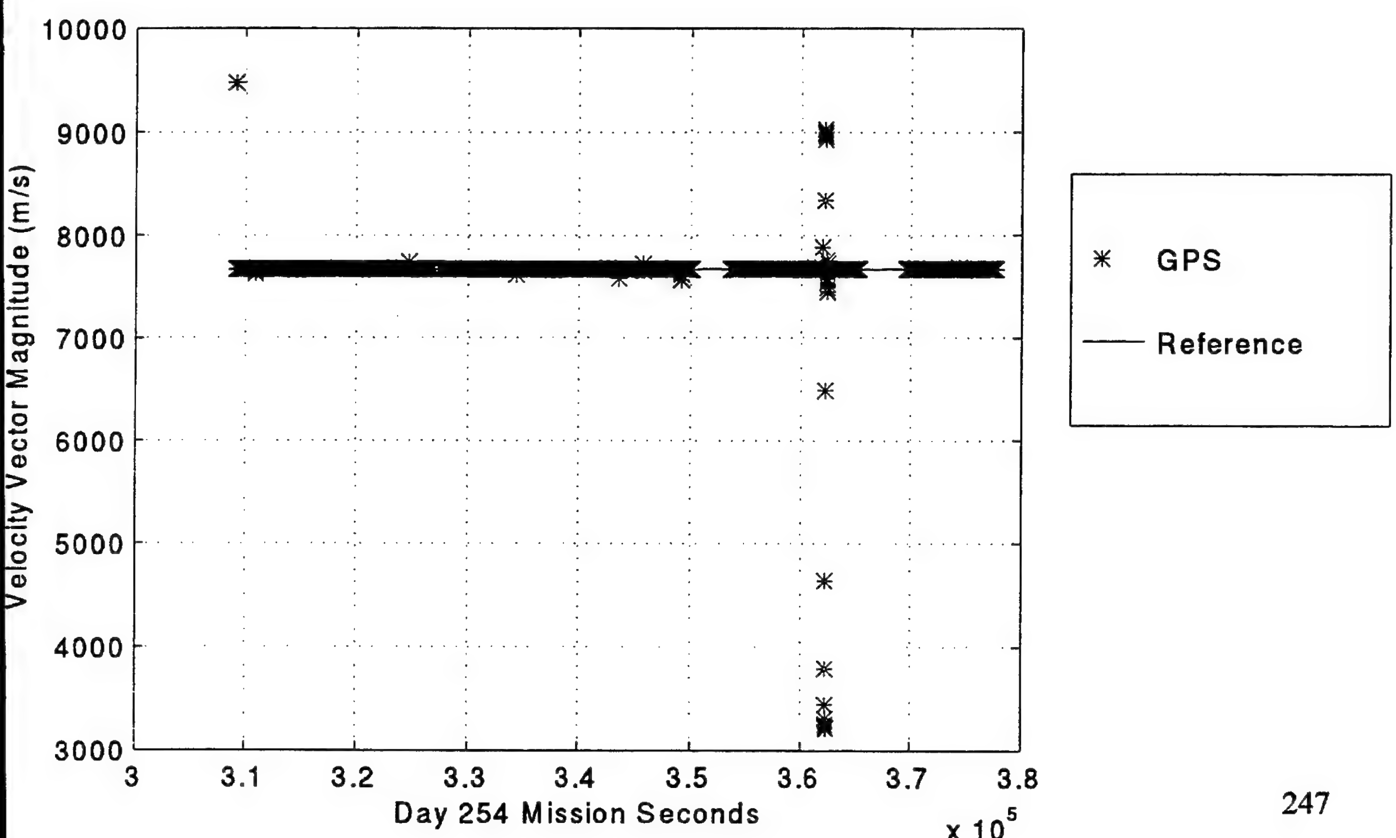
-15.65 / -98.84

APPENDIX Q. DAY 254 MATLAB PLOTS

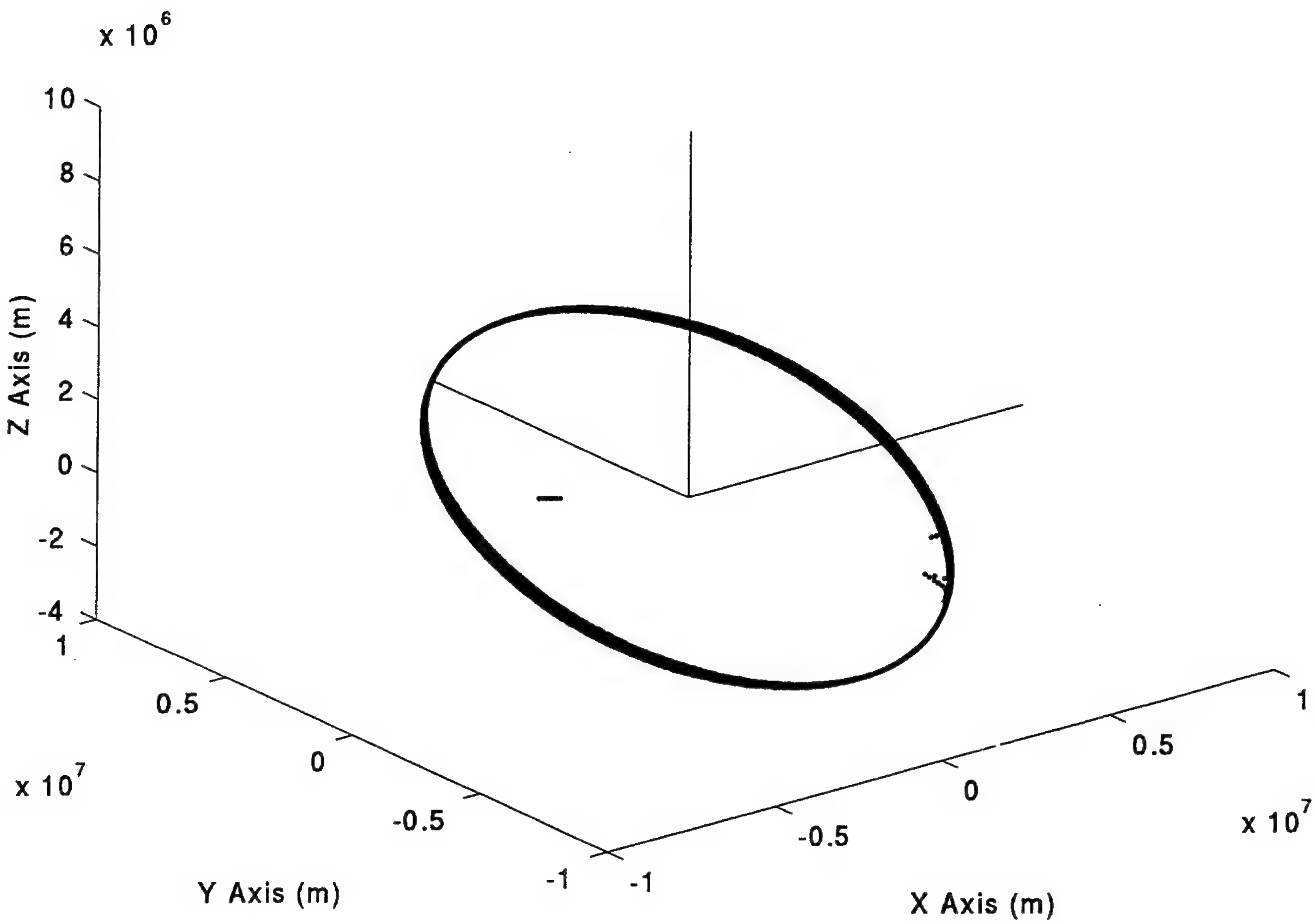

x 10^7
X Position (m)
Day 254 Mission Seconds
x 10^5
x 10^7
Y Position (m)
Day 254 Mission Seconds
x 10^5
x 10^6
Z Position (m)
Day 254 Mission Seconds
x 10^5
GPS
Reference


x 10^4
X Velocity (m/s)
1
0.5
0
-0.5
-1
3
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
Day 254 Mission Seconds
x 10^5
x 10^4
Y Velocity (m/s)
Day 254 Mission Seconds
x 10^5
Z Velocity (m/s)
4000
2000
0
-2000
-4000
Day 254 Mission Seconds
x 10^5
GPS
Reference

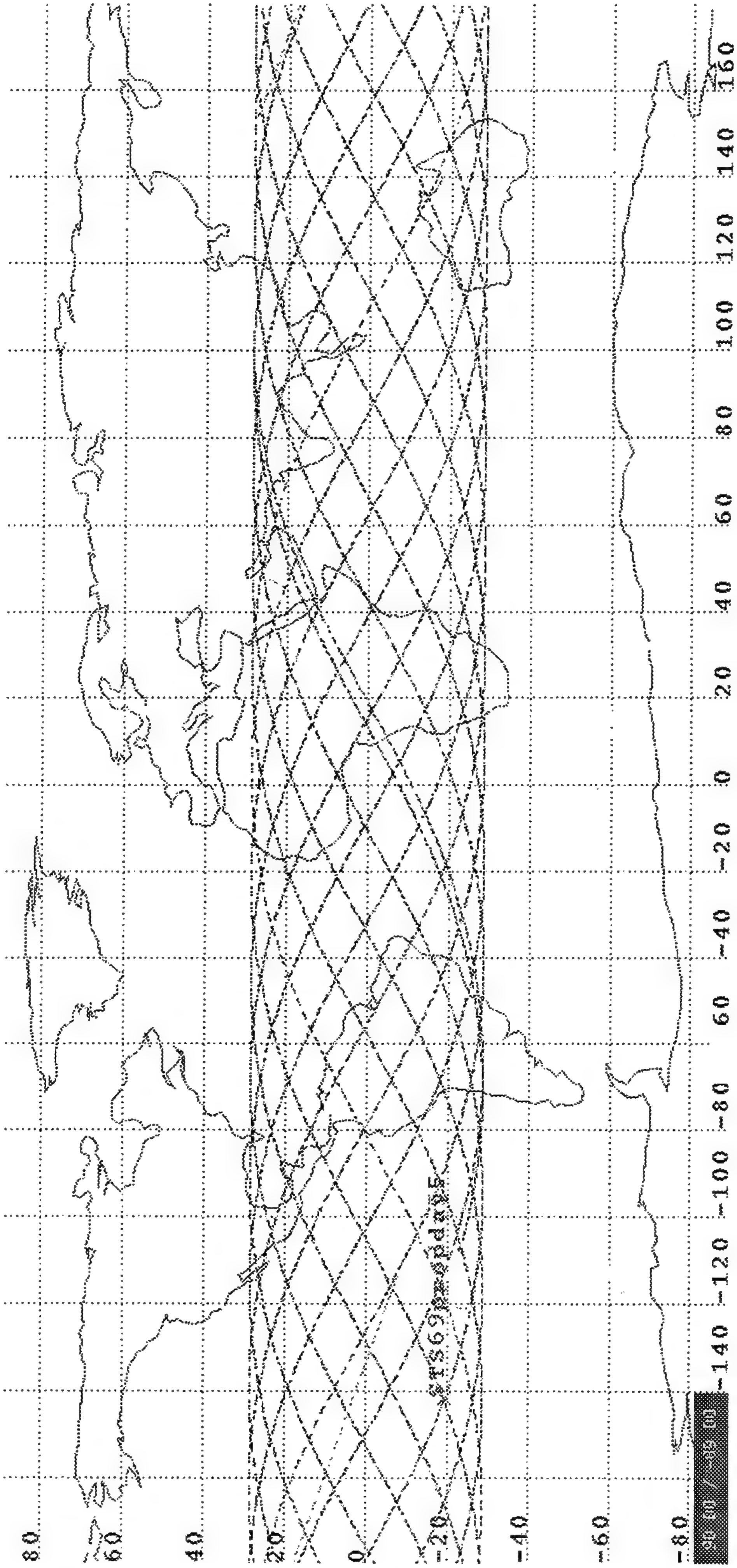

x 10^6
7
6.5
6
5.5
Position Vector Magnitude (Vehicle Altitude) (m)
3
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
Day 254 Mission Seconds
x 10^5

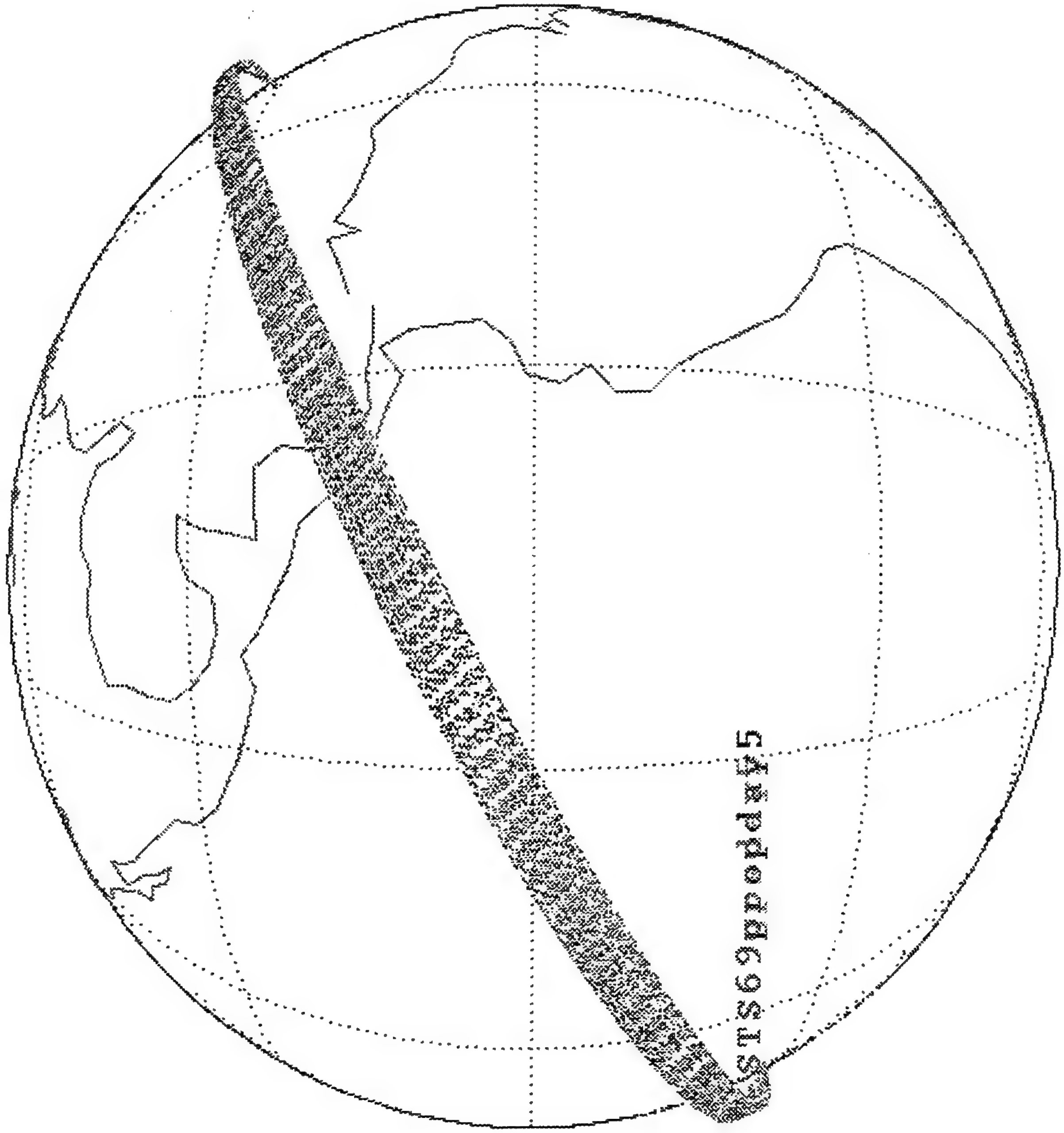

10000
9000
8000
7000
6000
5000
4000
3000
Velocity Vector Magnitude (m/s)
3
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
Day 254 Mission Seconds
x 10^5
GPS
Reference

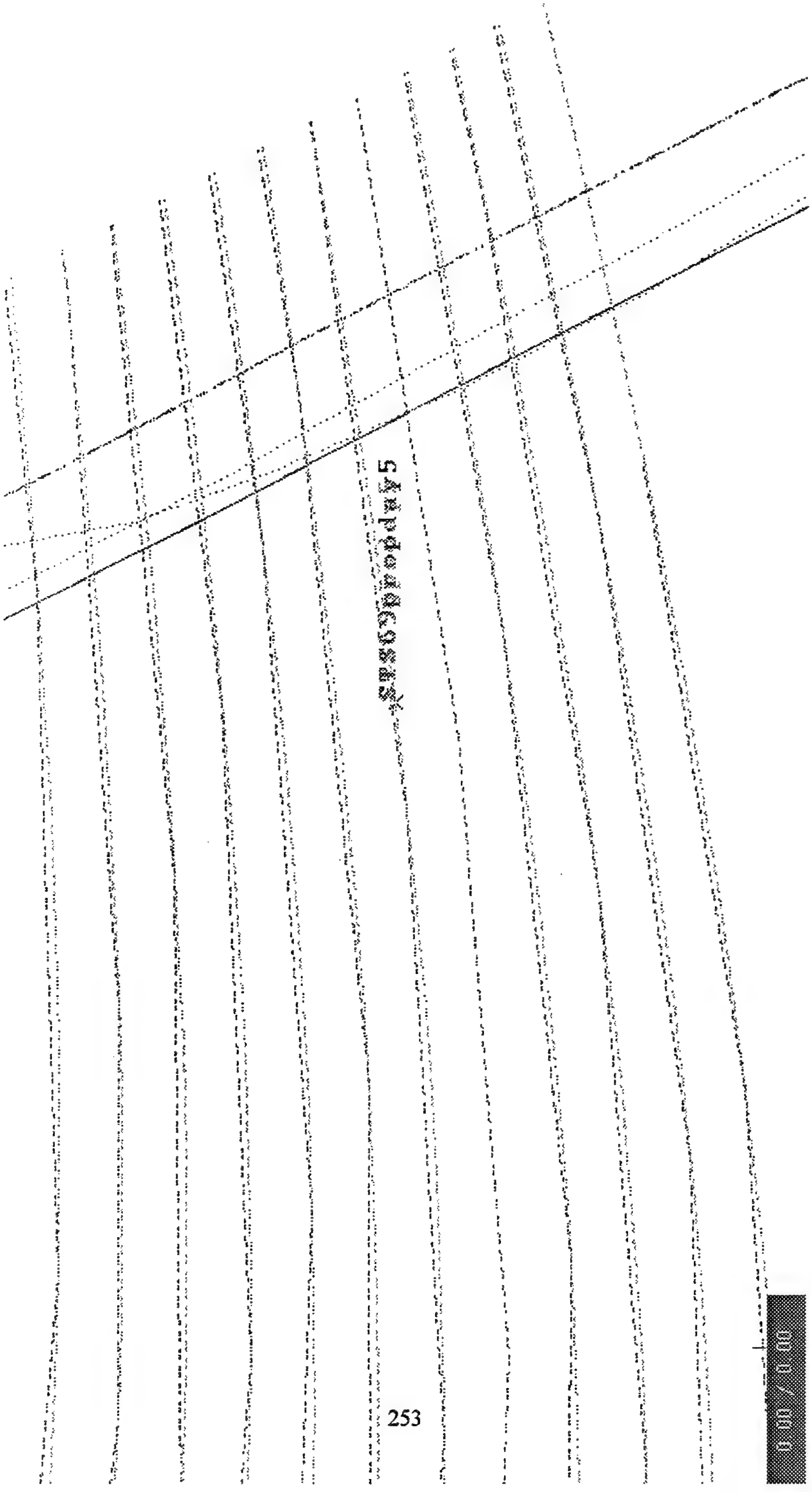
GPS Orbit for Day 254 in J2000 Coordinates

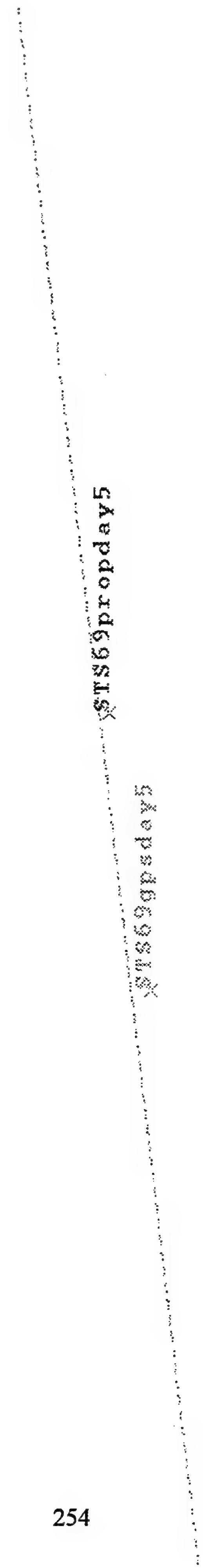


APPENDIX R. DAY 255 STK PLOTS

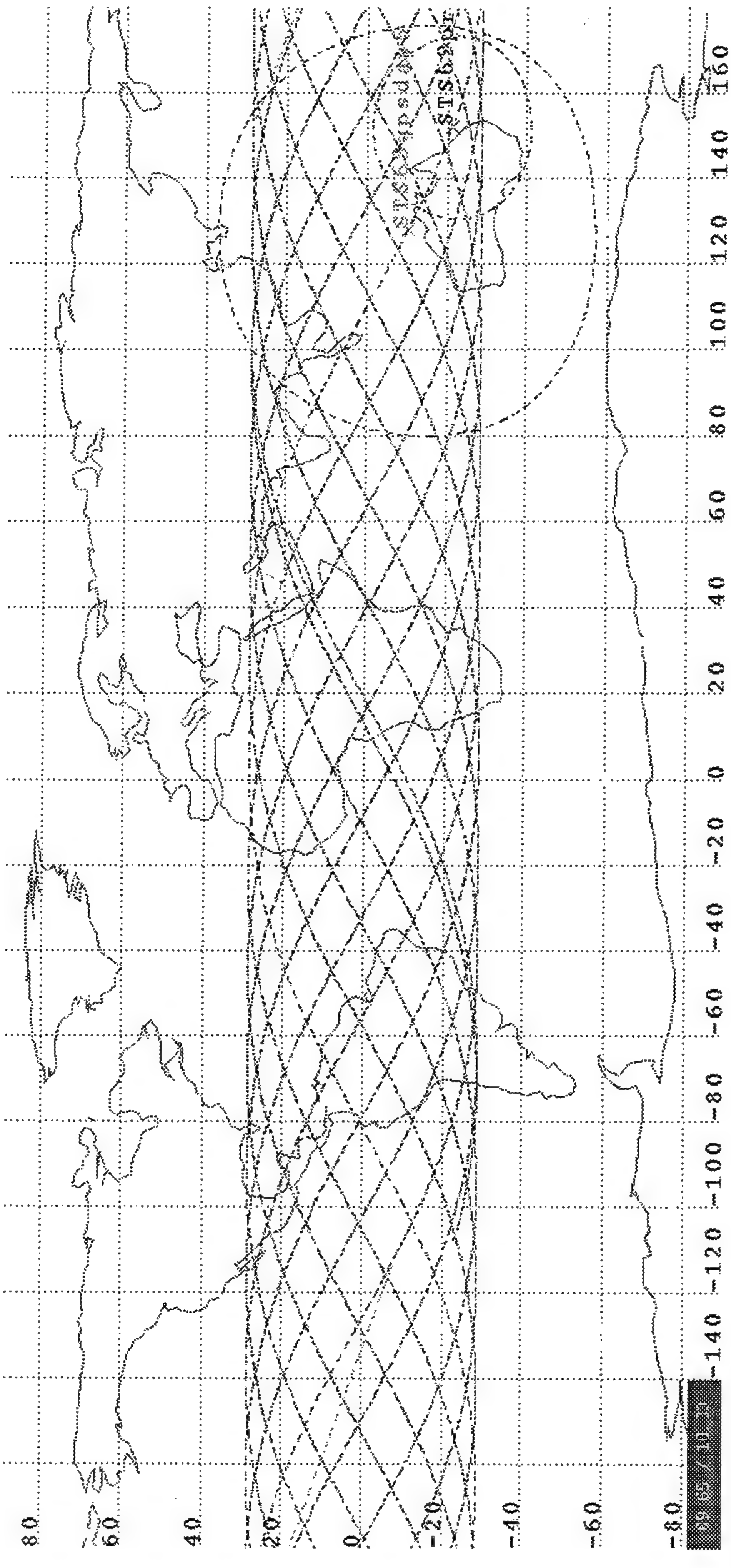

80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

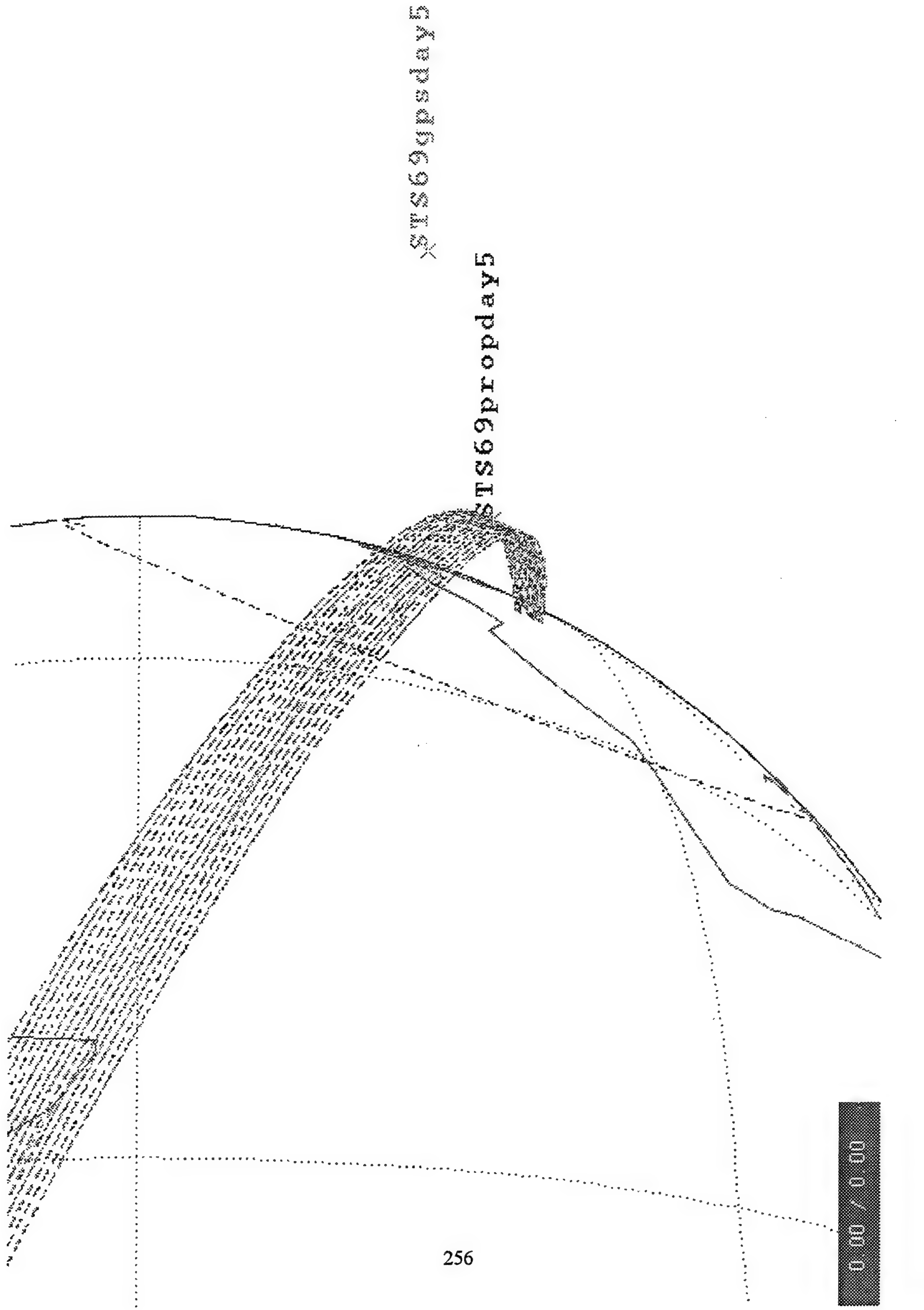

STS69prodxy5



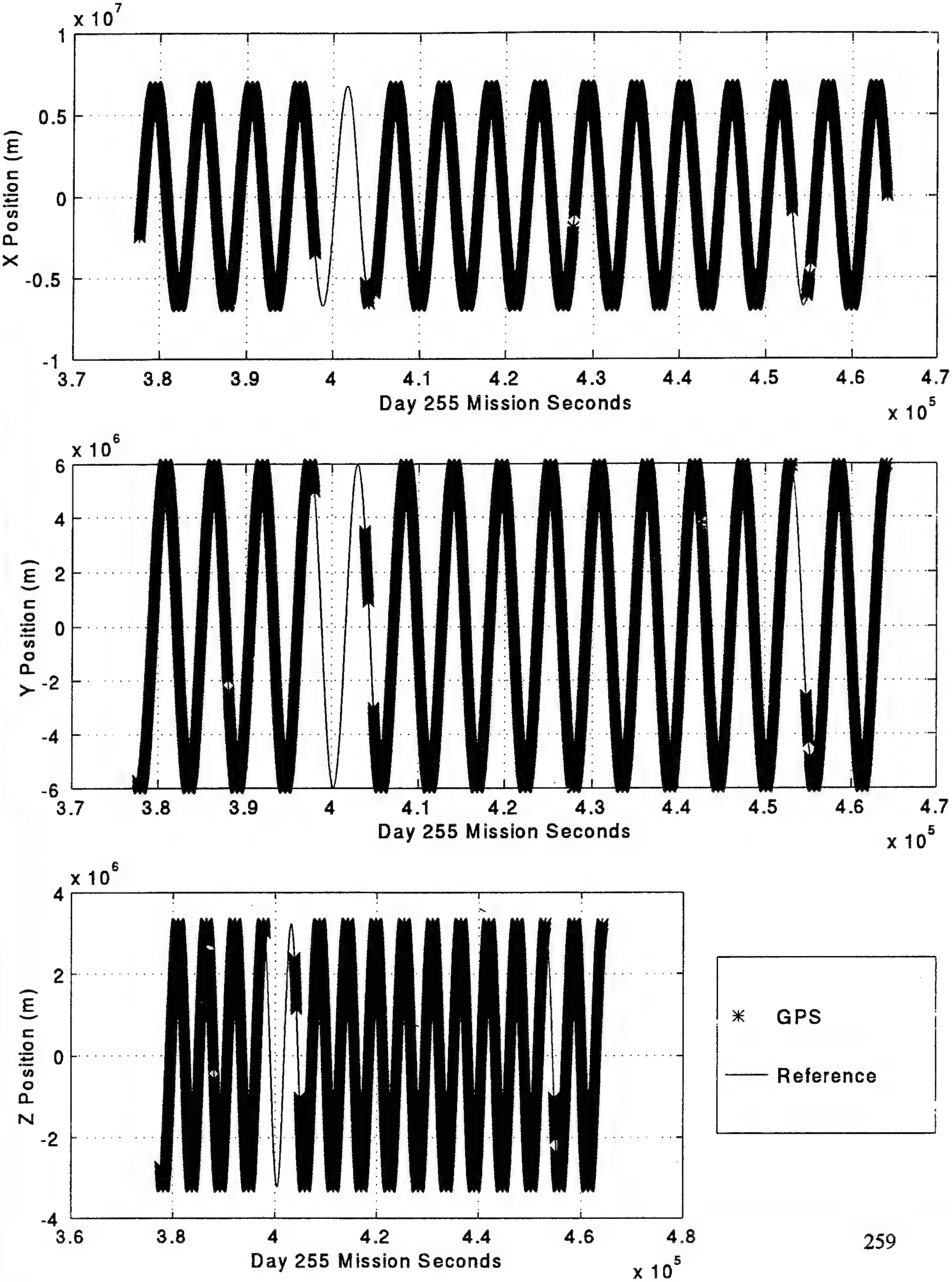


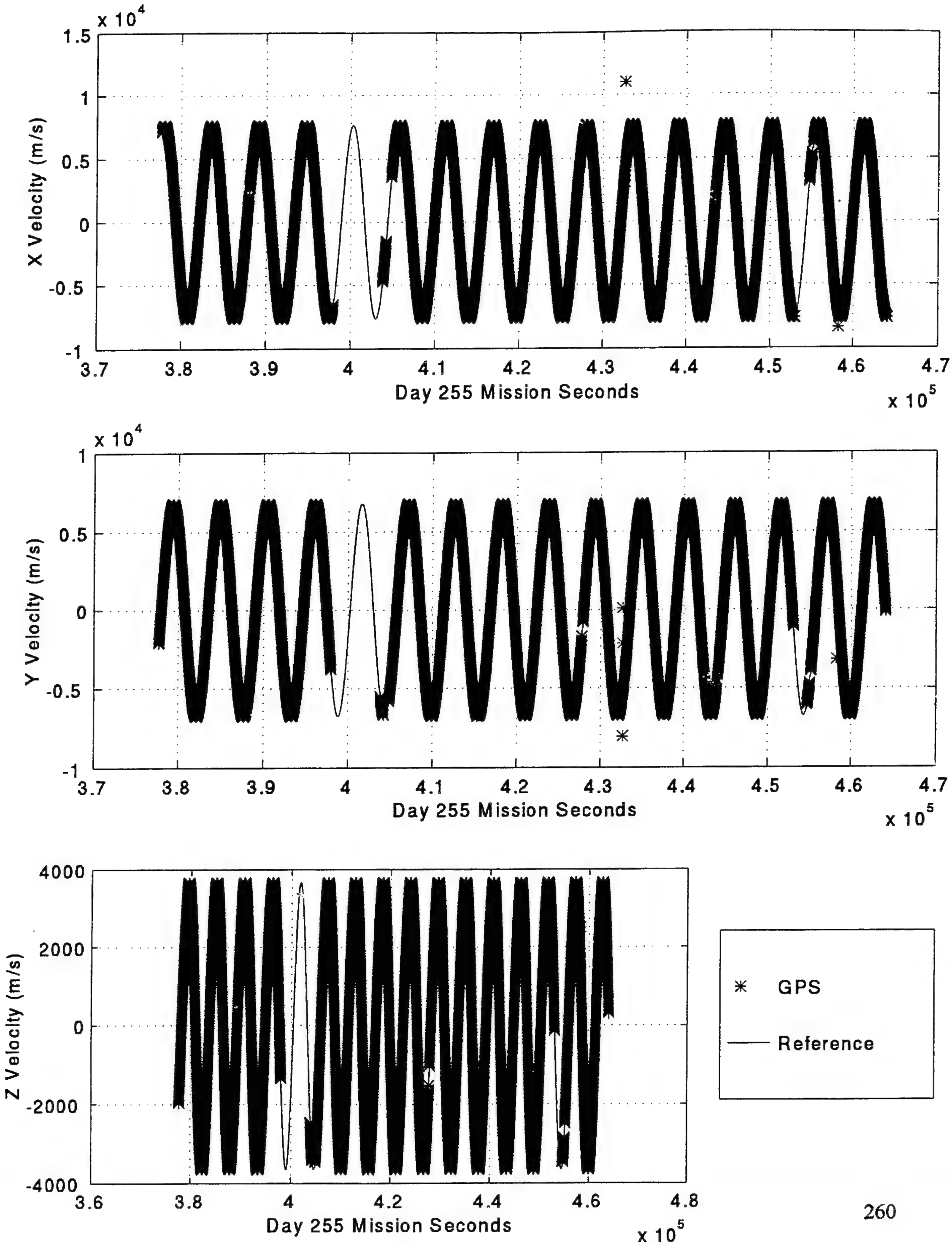
STS69propday5
STS69gpsday5

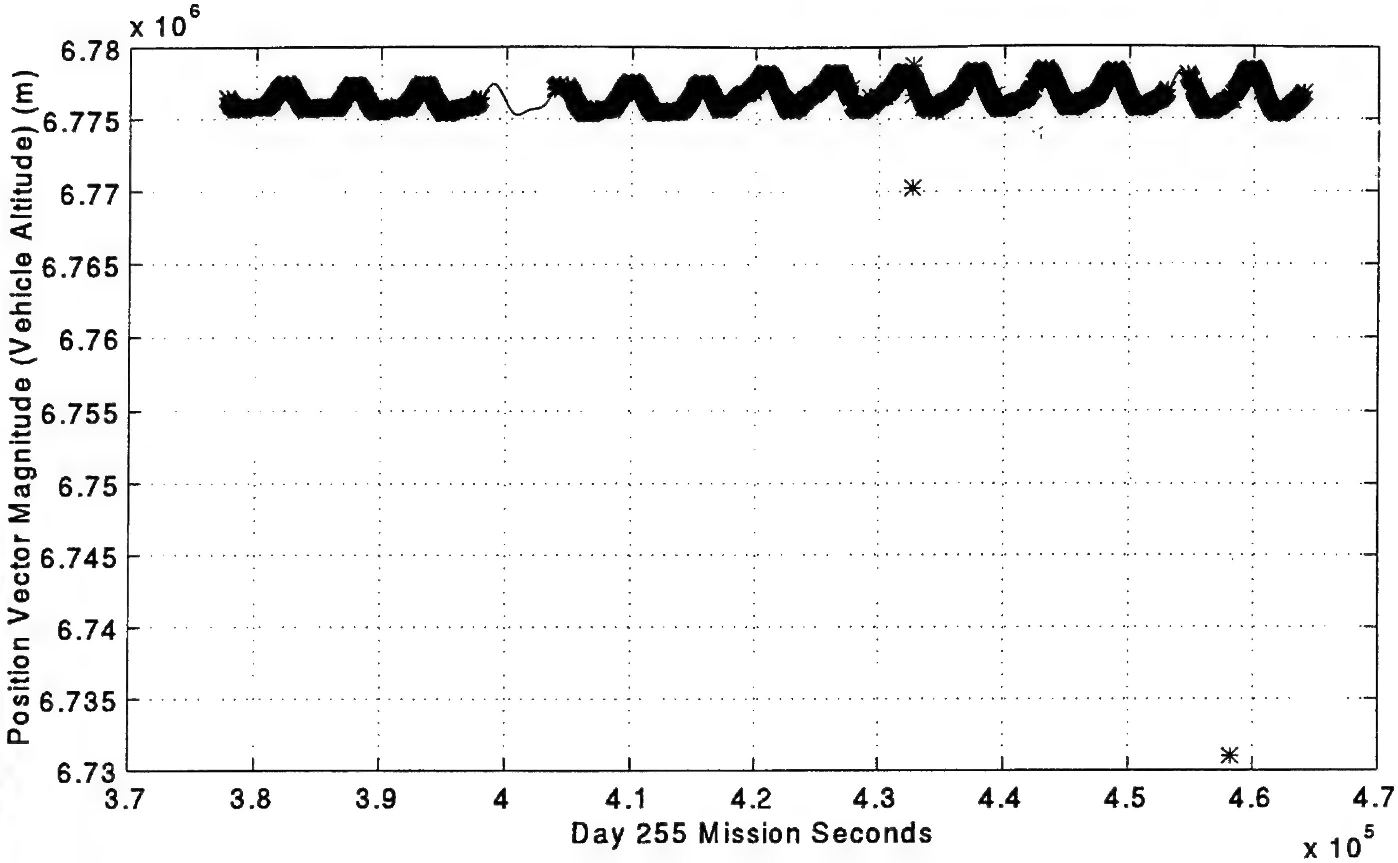

80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

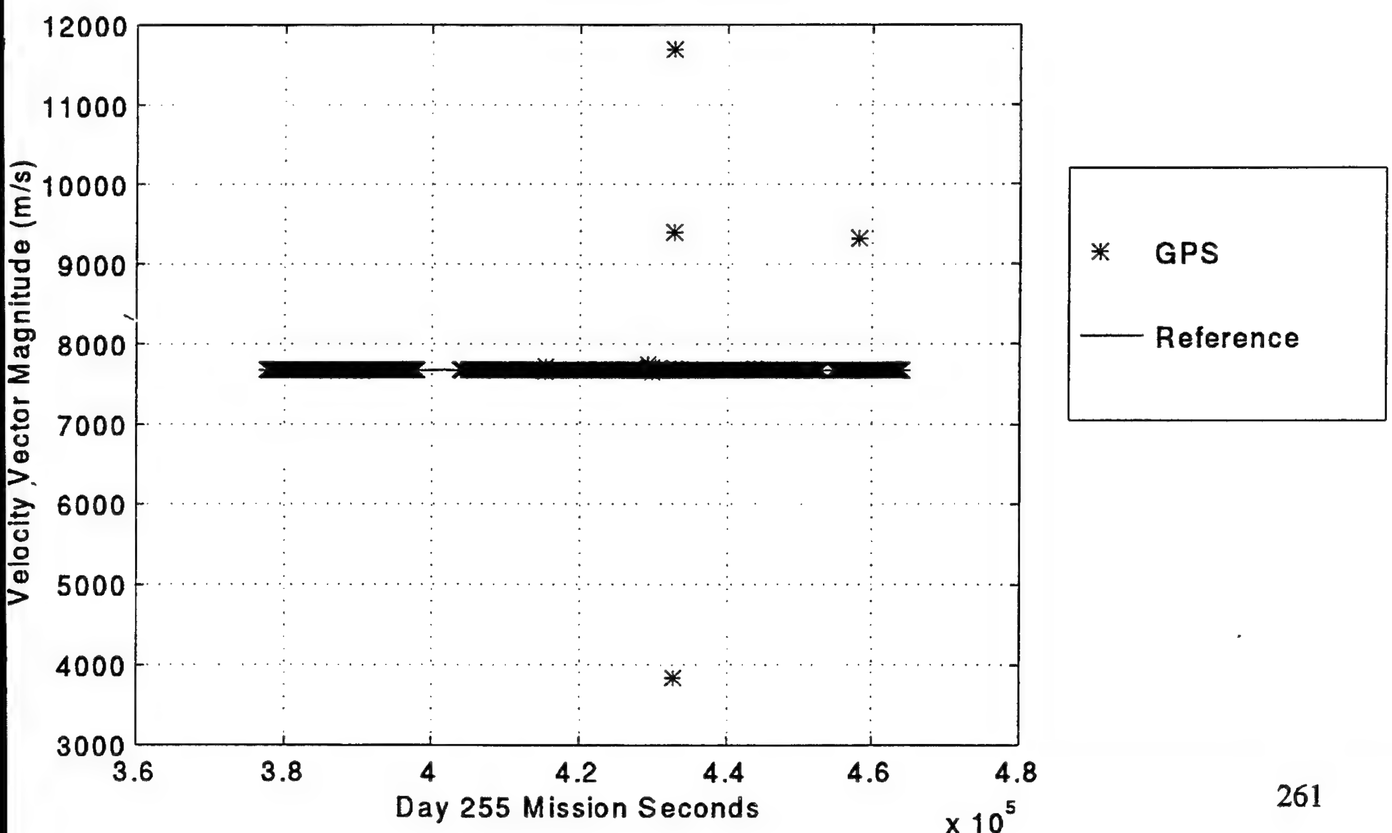

STS69gpsday5
STS69propday5
0.00 / 0.00

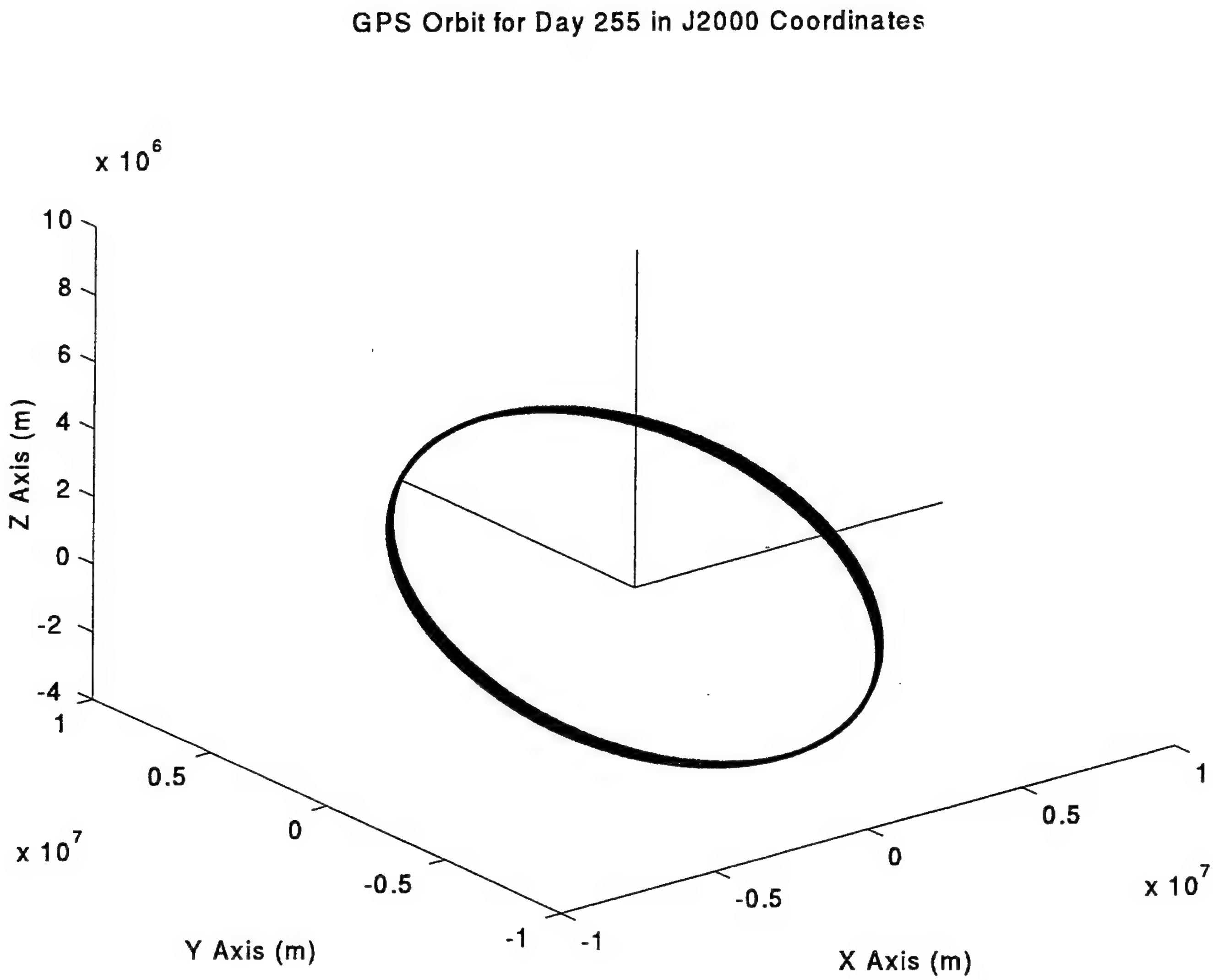
APPENDIX S. DAY 255 MATLAB PLOTS


x 10^7
1
0.5
0
-0.5
-1
X Position (m)
3.7 3.8 3.9 4 4.1 4.2 4.3 4.4 4.5 4.6 4.7
Day 255 Mission Seconds
x 10^5
x 10^6
6
4
2
0
-2
-4
-6
Y Position (m)
3.7 3.8 3.9 4 4.1 4.2 4.3 4.4 4.5 4.6 4.7
Day 255 Mission Seconds
x 10^5
x 10^6
4
2
0
-2
-4
Z Position (m)
3.6 3.8 4 4.2 4.4 4.6 4.8
Day 255 Mission Seconds
x 10^5
GPS
Reference

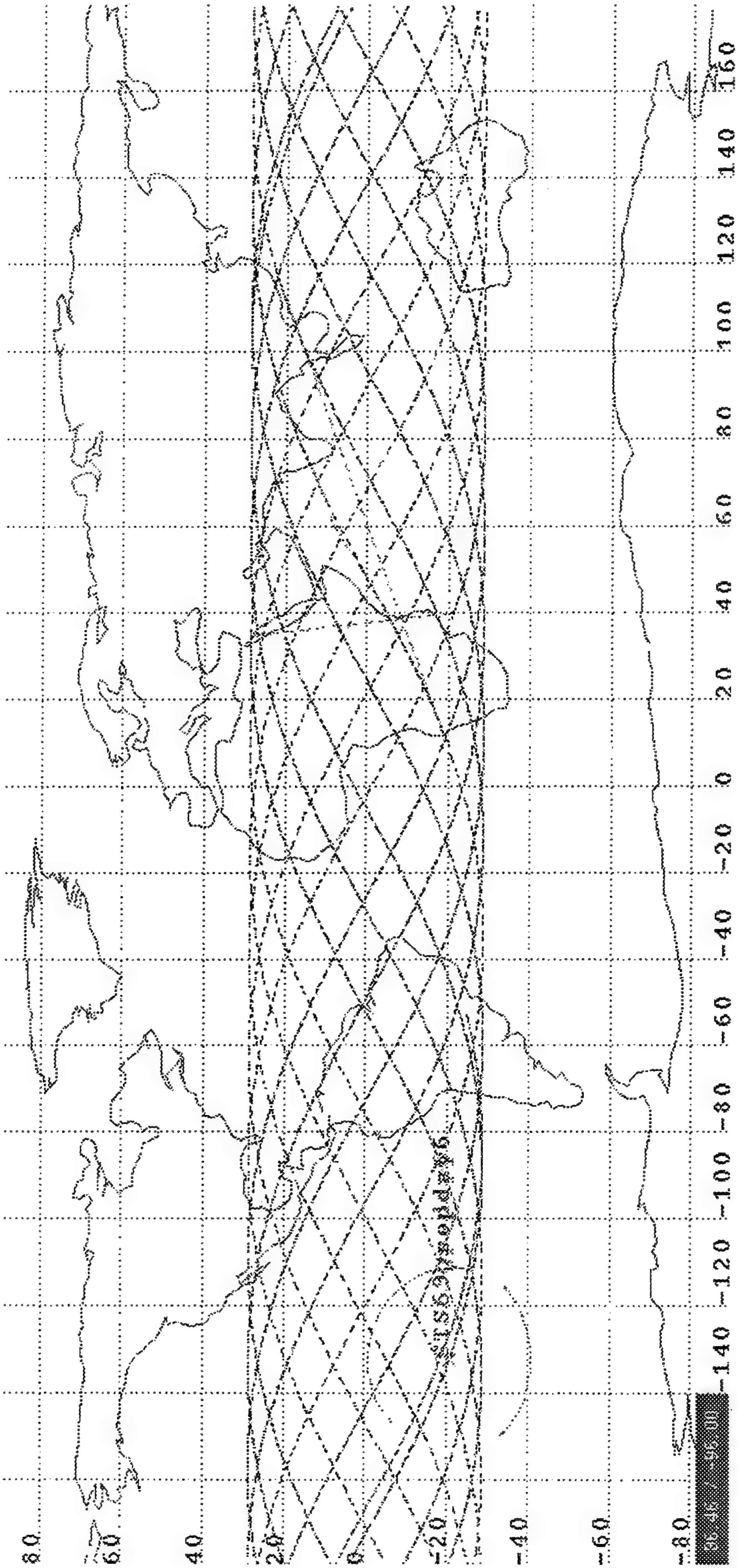

x 10^4
1.5
1
0.5
0
-0.5
-1
X Velocity (m/s)
3.7 3.8 3.9 4 4.1 4.2 4.3 4.4 4.5 4.6 4.7
Day 255 Mission Seconds
x 10^5
x 10^4
1
0.5
0
-0.5
-1
Y Velocity (m/s)
3.7 3.8 3.9 4 4.1 4.2 4.3 4.4 4.5 4.6 4.7
Day 255 Mission Seconds
x 10^5
4000
2000
0
-2000
-4000
Z Velocity (m/s)
3.6 3.8 4 4.2 4.4 4.6 4.8
Day 255 Mission Seconds
x 10^5
GPS
Reference

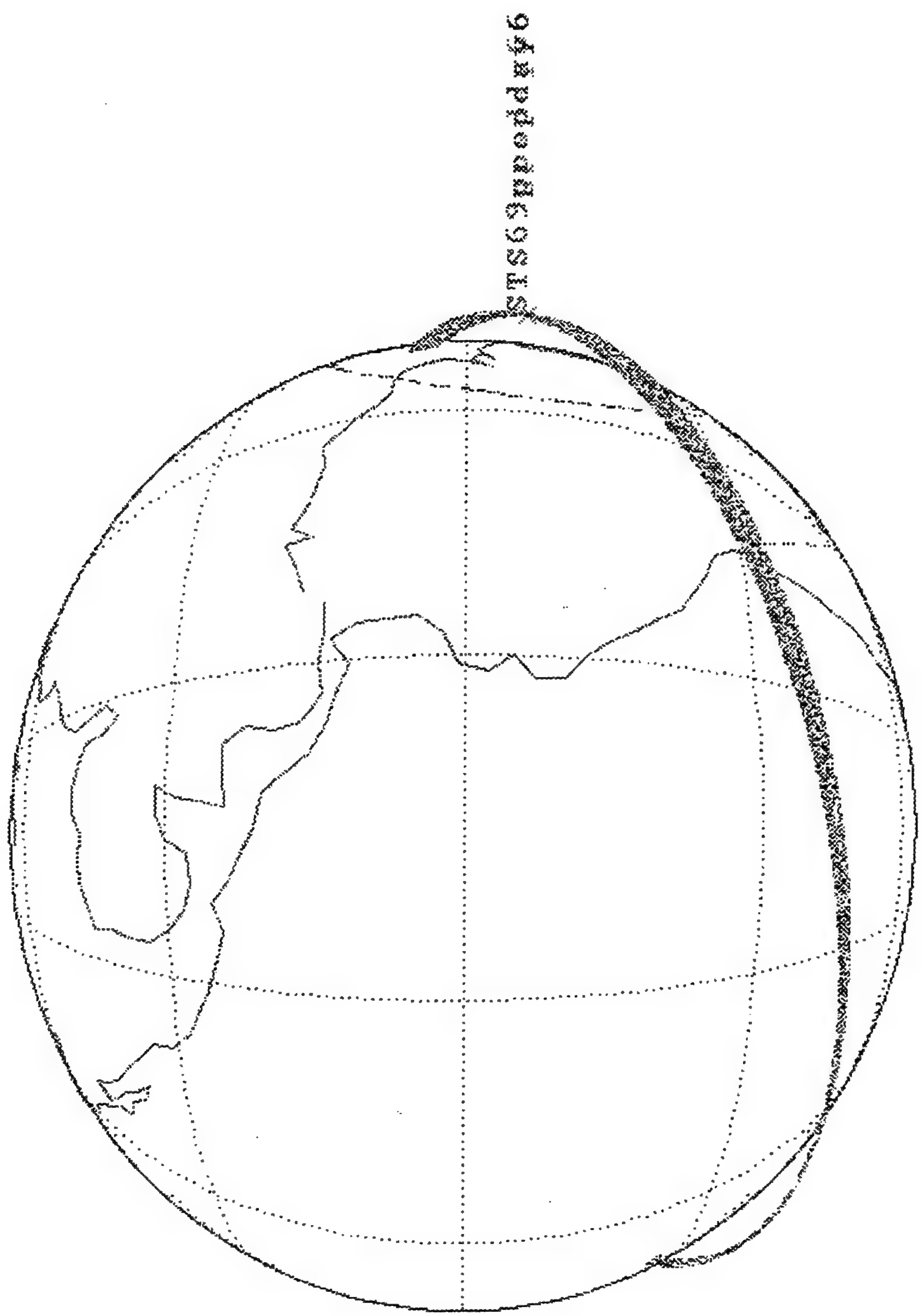

x 10^6
6.78
6.775
6.77
6.765
6.76
6.755
6.75
6.745
6.74
6.735
6.73
Position Vector Magnitude (Vehicle Altitude) (m)
3.7
3.8
3.9
4
4.1
4.2
4.3
4.4
4.5
4.6
4.7
Day 255 Mission Seconds
x 10^5


12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
Velocity Vector Magnitude (m/s)
3.6
3.8
4
4.2
4.4
4.6
4.8
Day 255 Mission Seconds
x 10^5
GPS
Reference


GPS Orbit for Day 255 in J2000 Coordinates
x 10^6
10
8
6
4
2
0
-2
-4
Z Axis (m)
1
0.5
0
-0.5
-1
x 10^7
Y Axis (m)
-1
-0.5
0
0.5
1
x 10^7
X Axis (m)

APPENDIX T. DAY 256 STK PLOTS

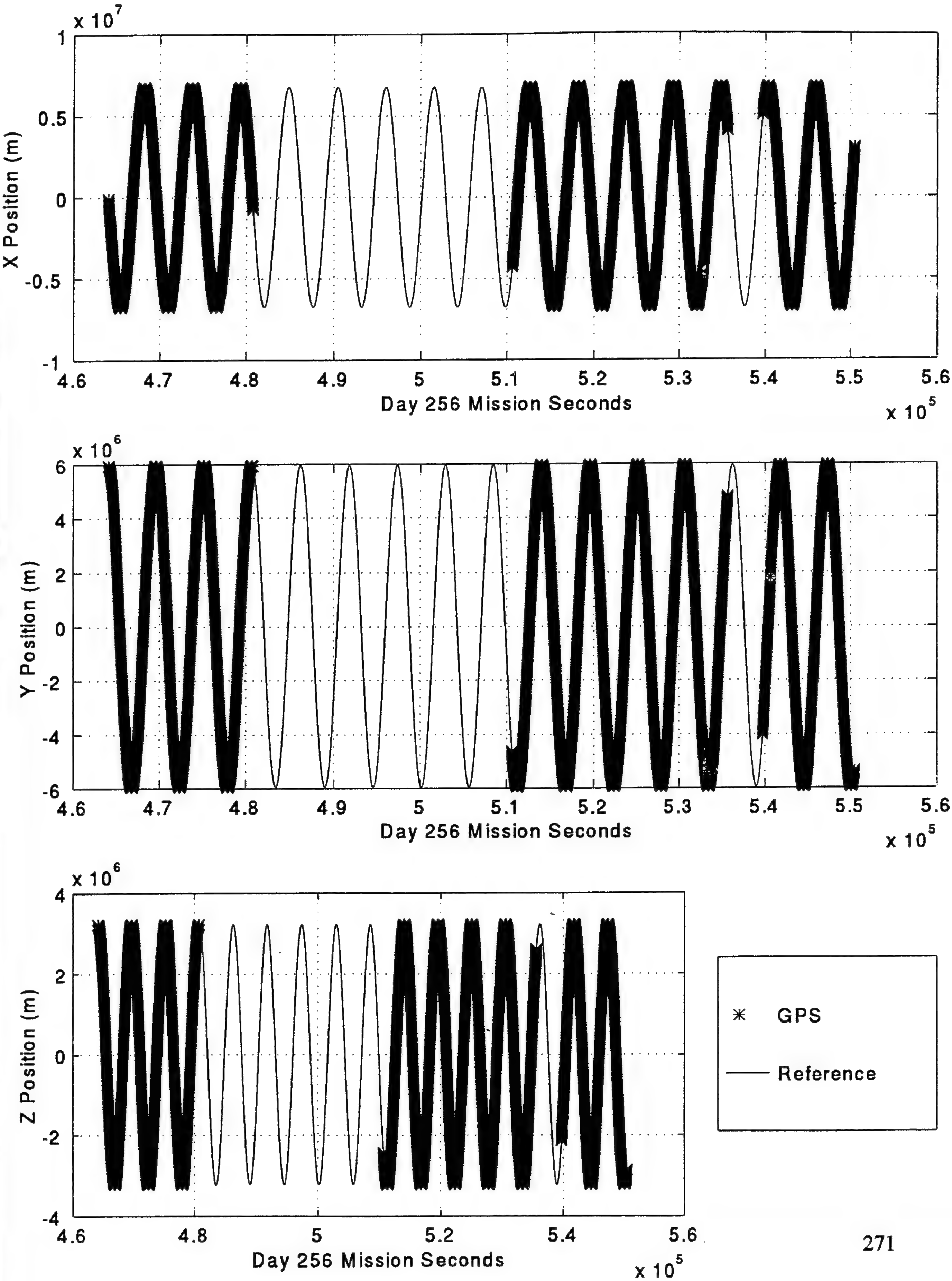

80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

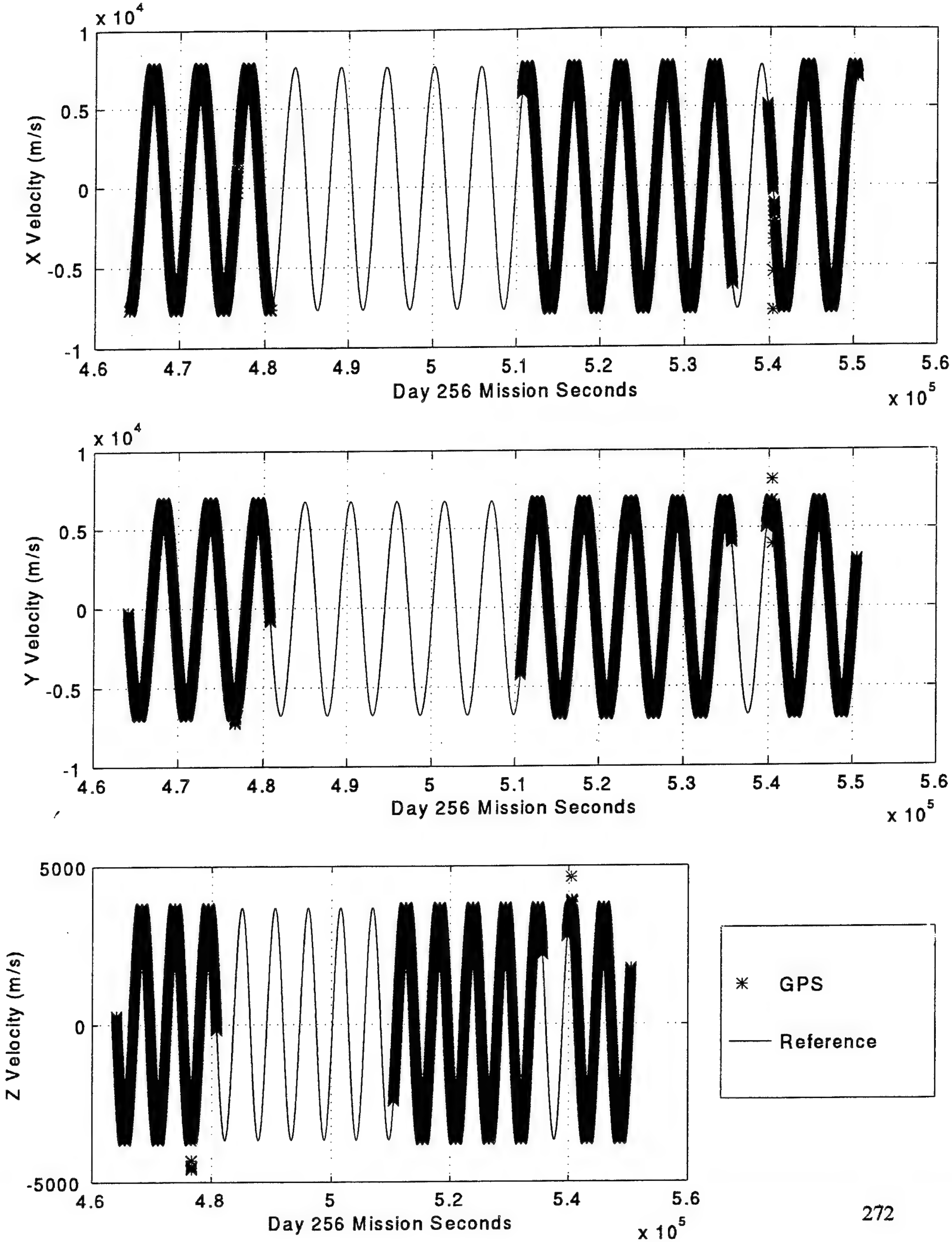


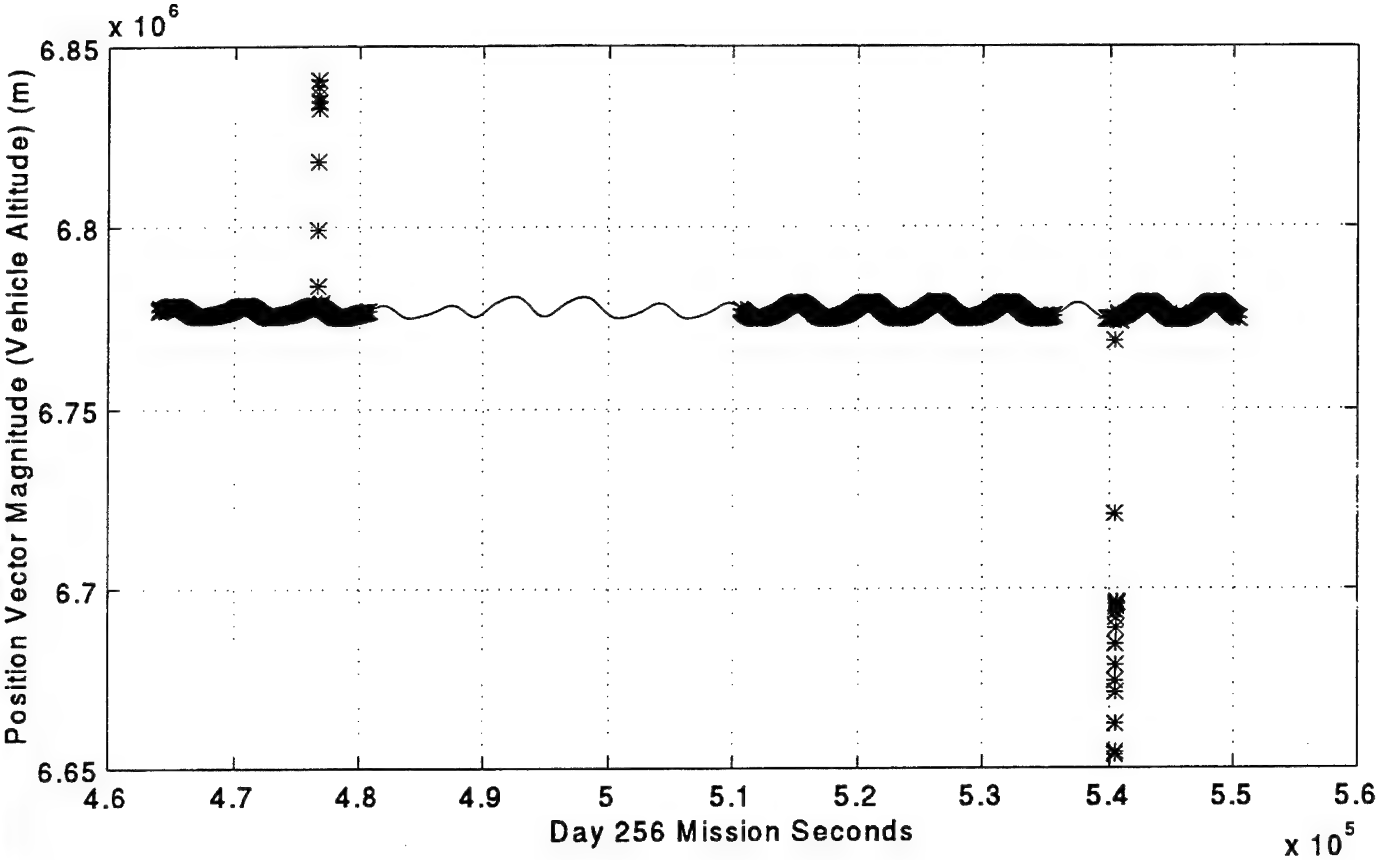
STS69propday6

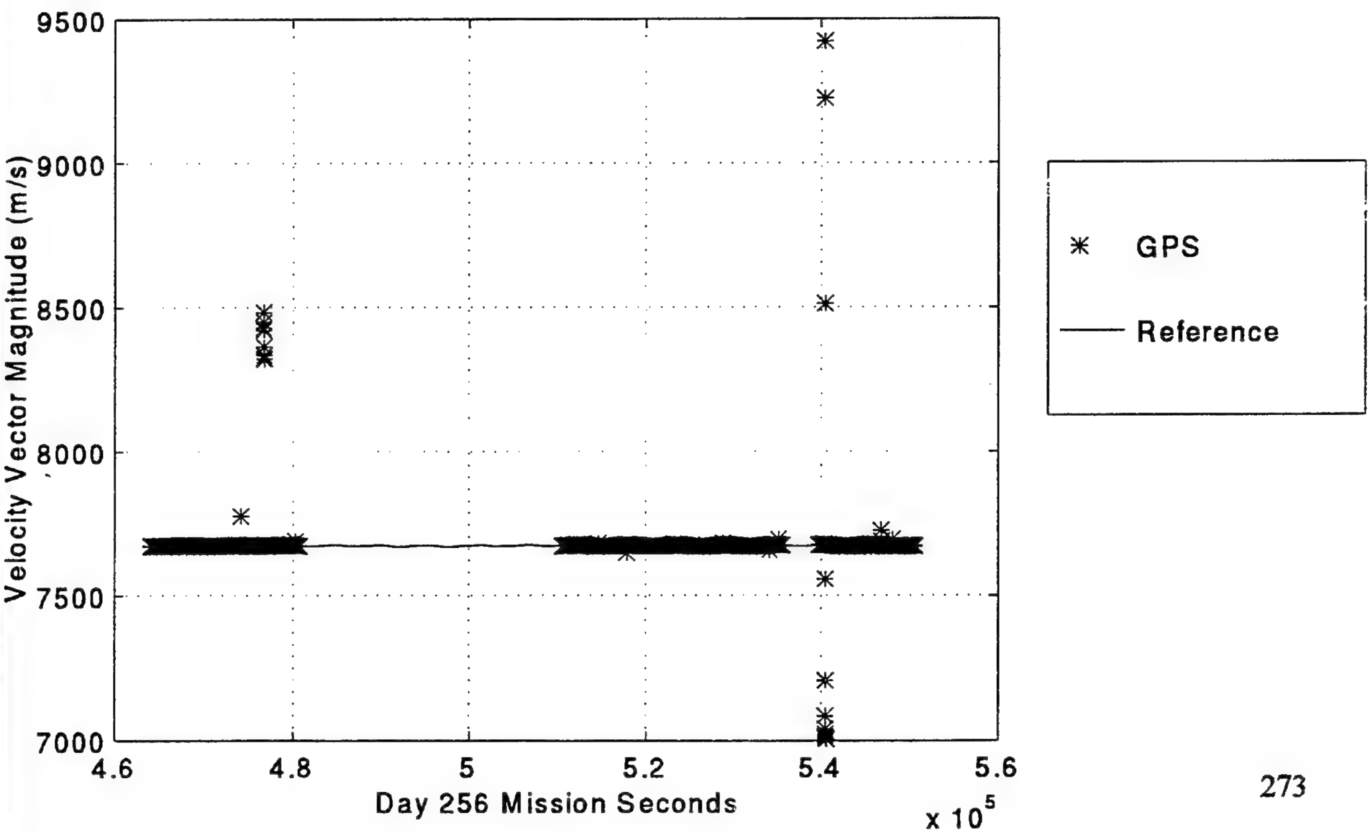
STS69gpsday6

APPENDIX U. DAY 256 MATLAB PLOTS

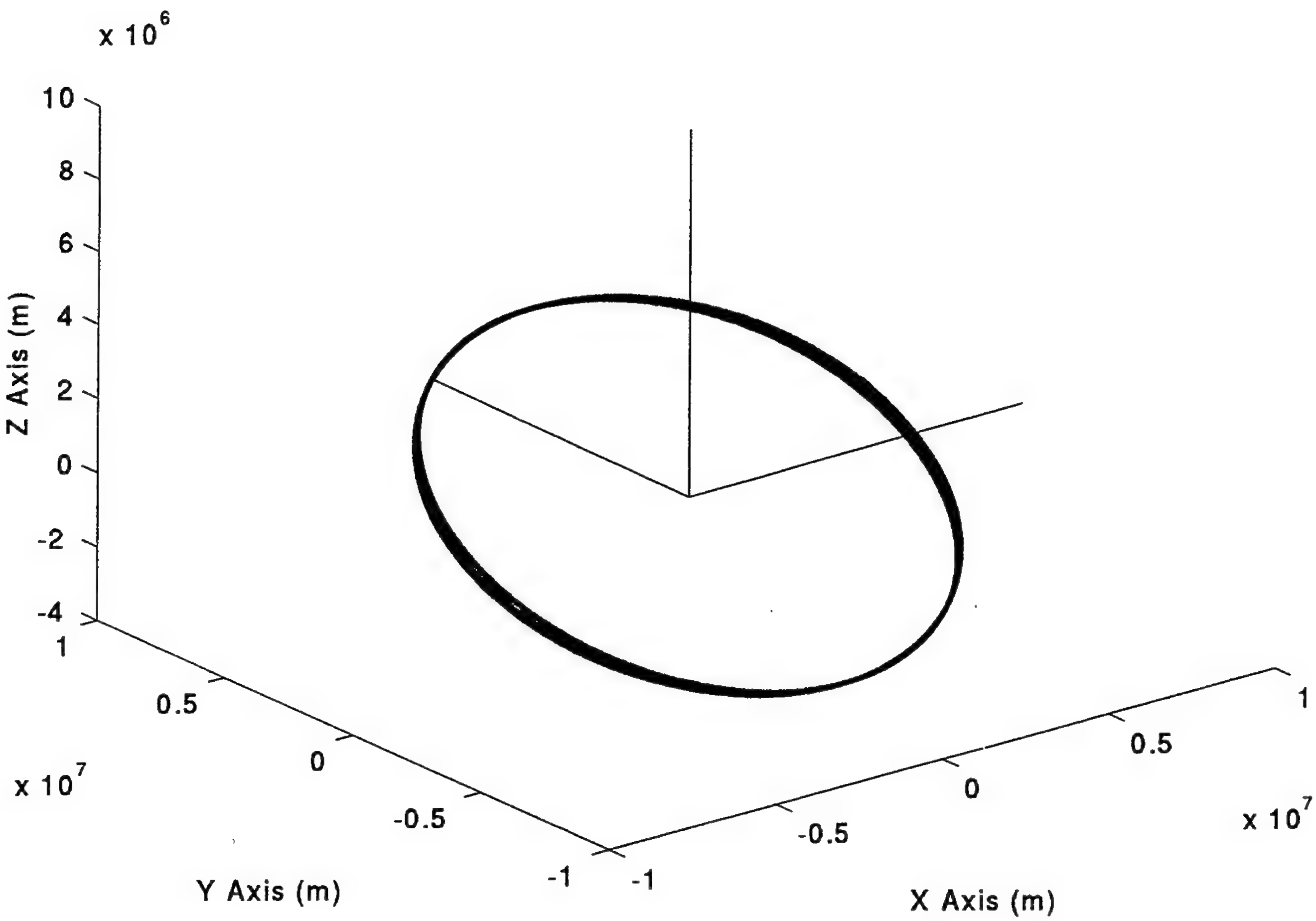

x 10^7
1
0.5
0
-0.5
-1
X Position (m)
4.6
4.7
4.8
4.9
5
5.1
5.2
5.3
5.4
5.5
5.6
Day 256 Mission Seconds
x 10^5
x 10^6
6
4
2
0
-2
-4
-6
Y Position (m)
Day 256 Mission Seconds
x 10^5
x 10^6
4
2
0
-2
-4
Z Position (m)
4.6
4.8
5
5.2
5.4
5.6
Day 256 Mission Seconds
x 10^5
GPS
Reference


x 10^4
X Velocity (m/s)
1
0.5
0
-0.5
-1
4.6
4.7
4.8
4.9
5
5.1
5.2
5.3
5.4
5.5
5.6
Day 256 Mission Seconds
x 10^5
x 10^4
Y Velocity (m/s)
1
0.5
0
-0.5
-1
4.6
4.7
4.8
4.9
5
5.1
5.2
5.3
5.4
5.5
5.6
Day 256 Mission Seconds
x 10^5
Z Velocity (m/s)
5000
0
-5000
4.6
4.8
5
5.2
5.4
5.6
Day 256 Mission Seconds
x 10^5
GPS
Reference

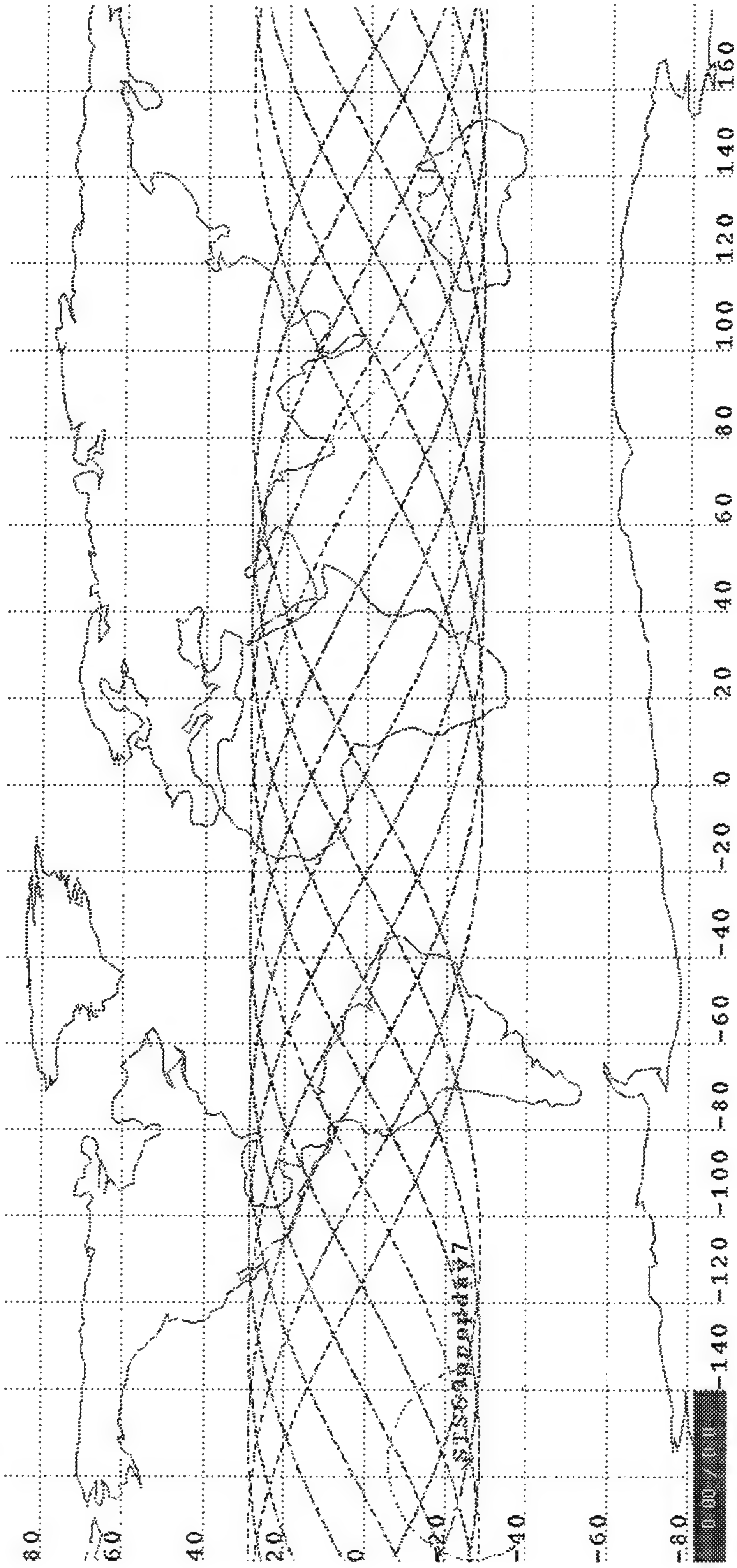

x 10^6
6.85
6.8
6.75
6.7
6.65
Position Vector Magnitude (Vehicle Altitude) (m)
4.6
4.7
4.8
4.9
5
5.1
5.2
5.3
5.4
5.5
5.6
Day 256 Mission Seconds
x 10^5

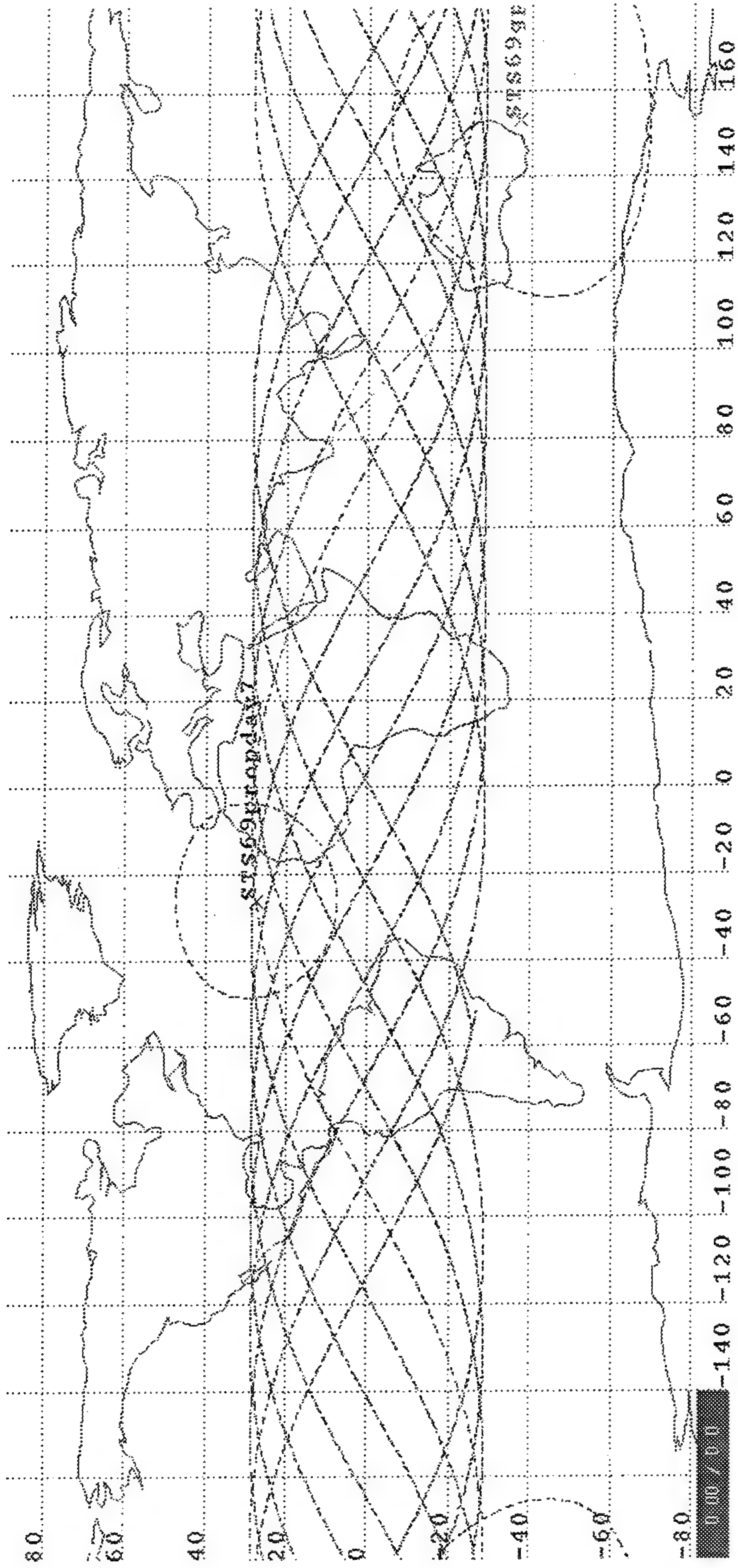

9500
9000
8500
8000
7500
7000
Velocity Vector Magnitude (m/s)
4.6
4.8
5
5.2
5.4
5.6
Day 256 Mission Seconds
x 10^5
GPS
Reference

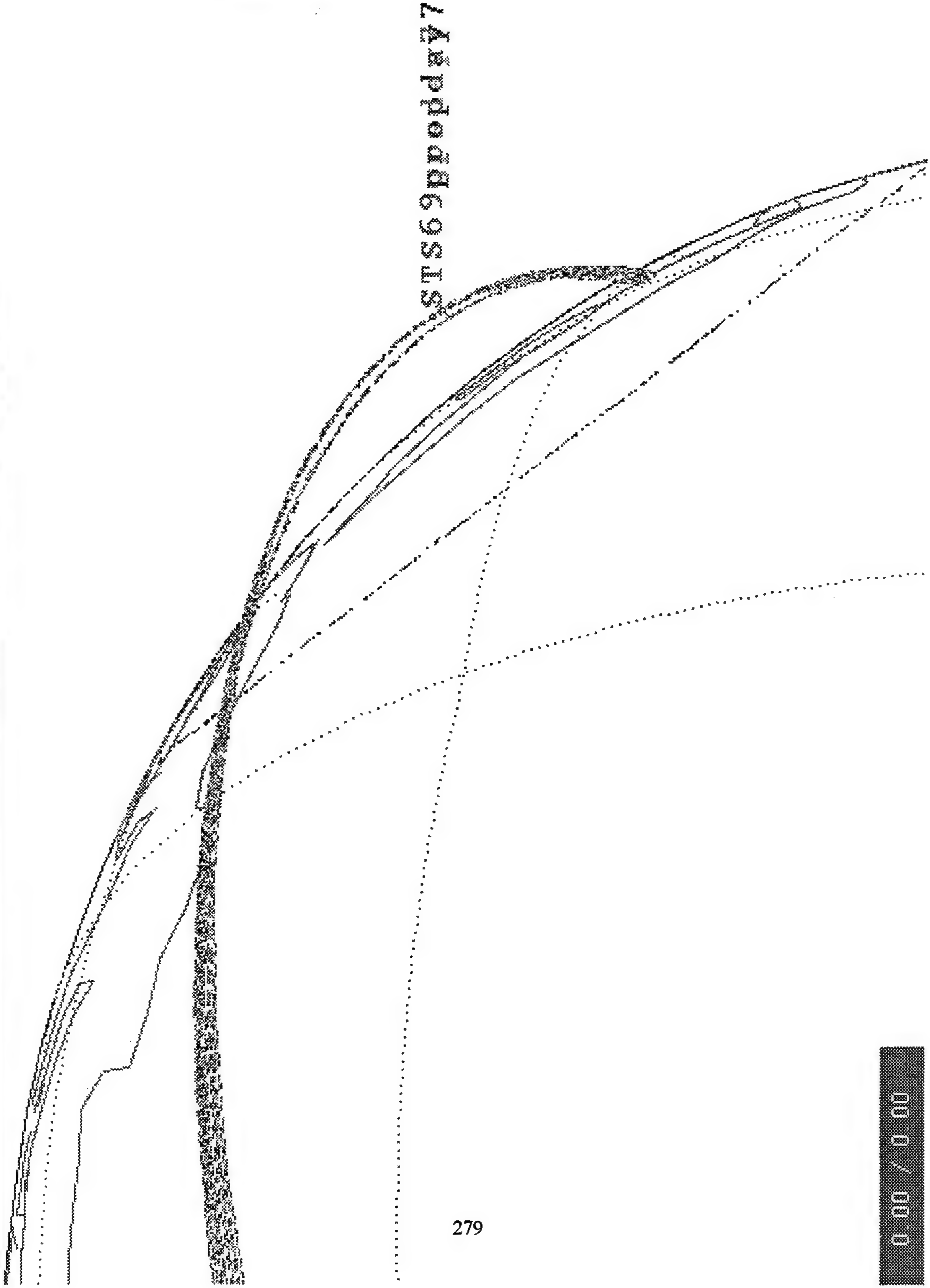
GPS Orbit for Day 256 in J2000 Coordinates

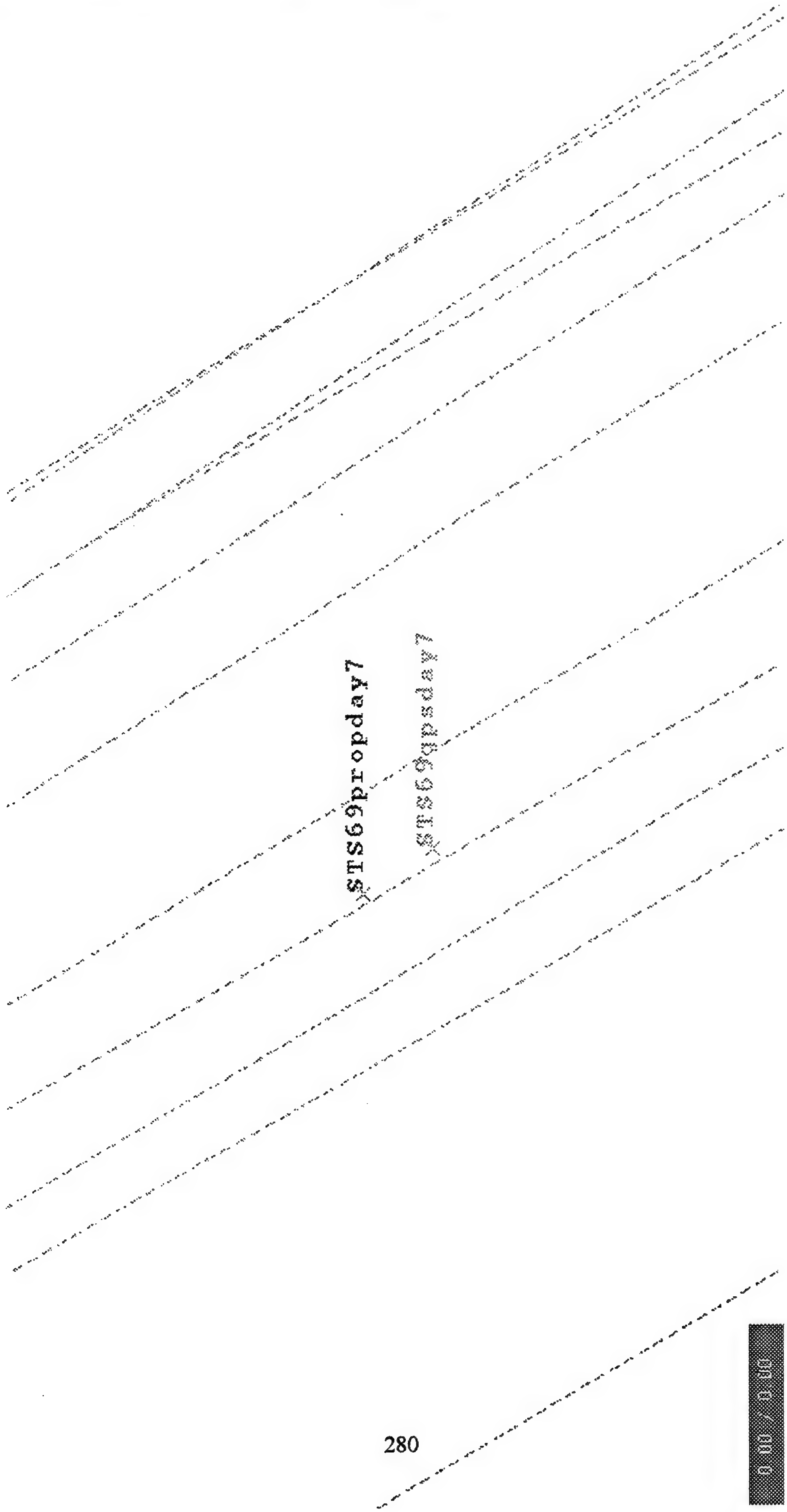


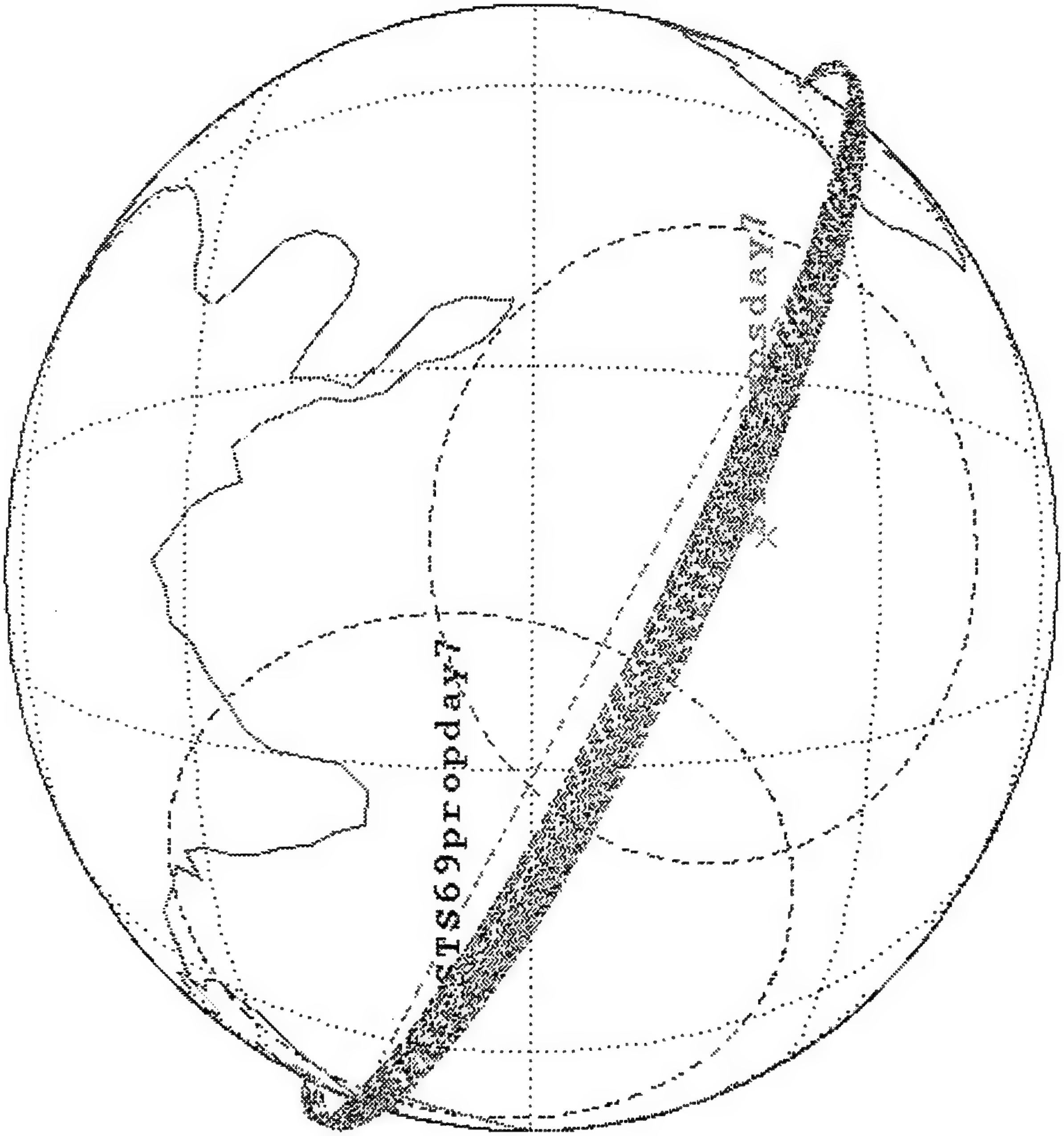
APPENDIX V. DAY 257 STK PLOTS

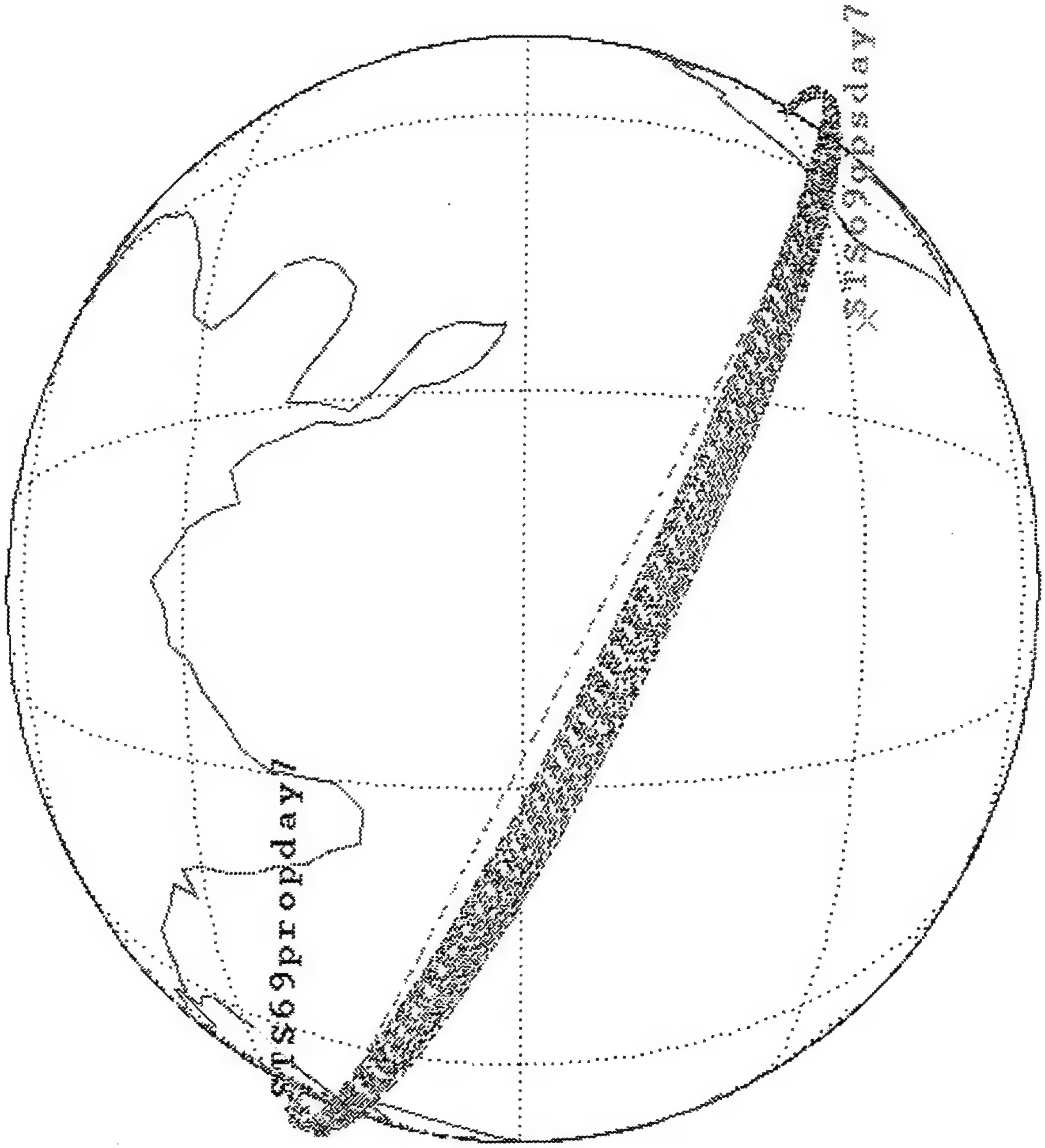

80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
STS6appnday7


STS69propday7
STS69ge
80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

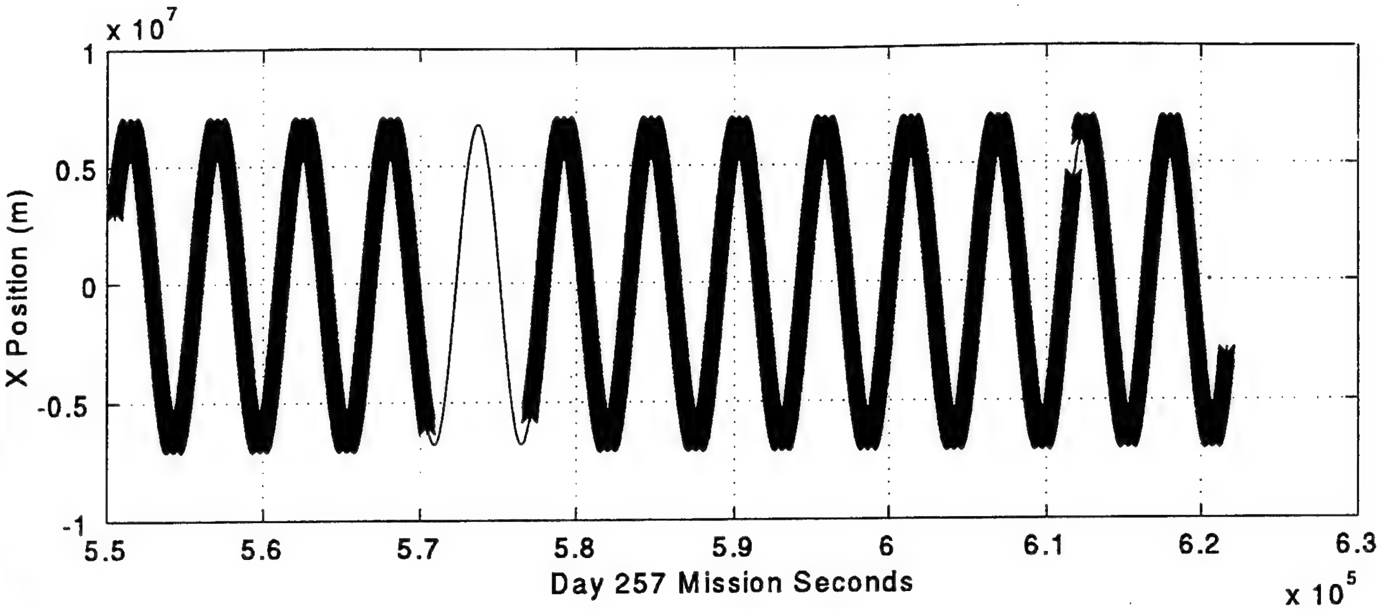

STS69
0.00 / 0.00

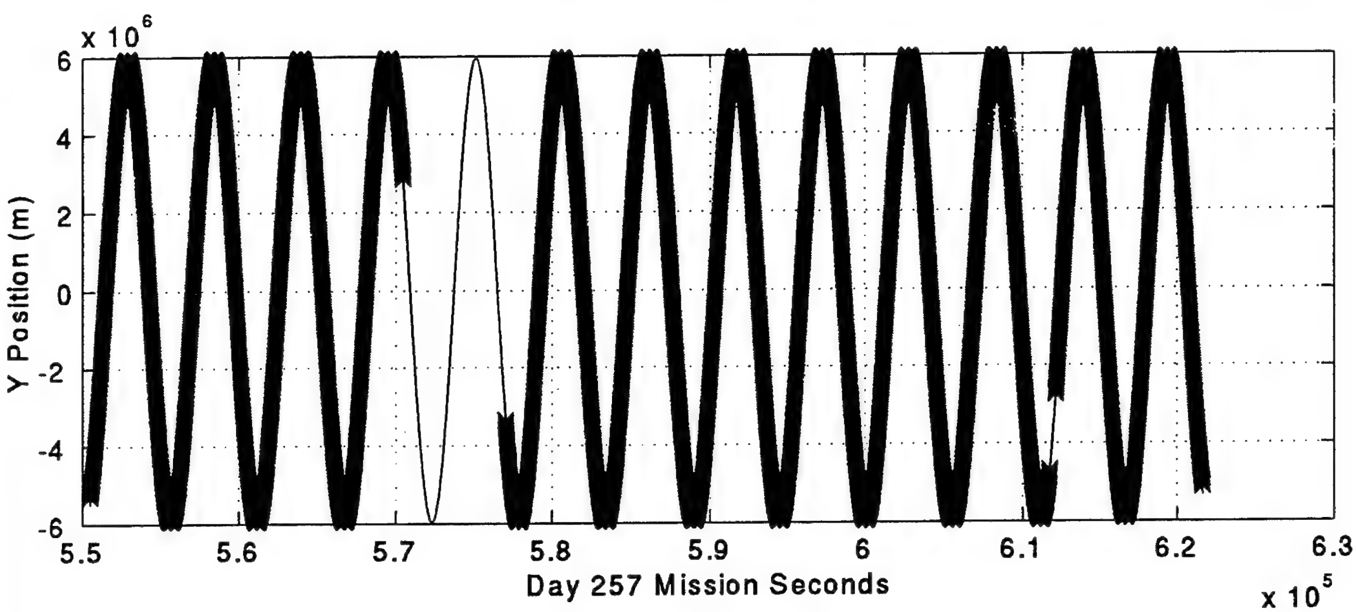

STS69propday7
STS69gpsday7

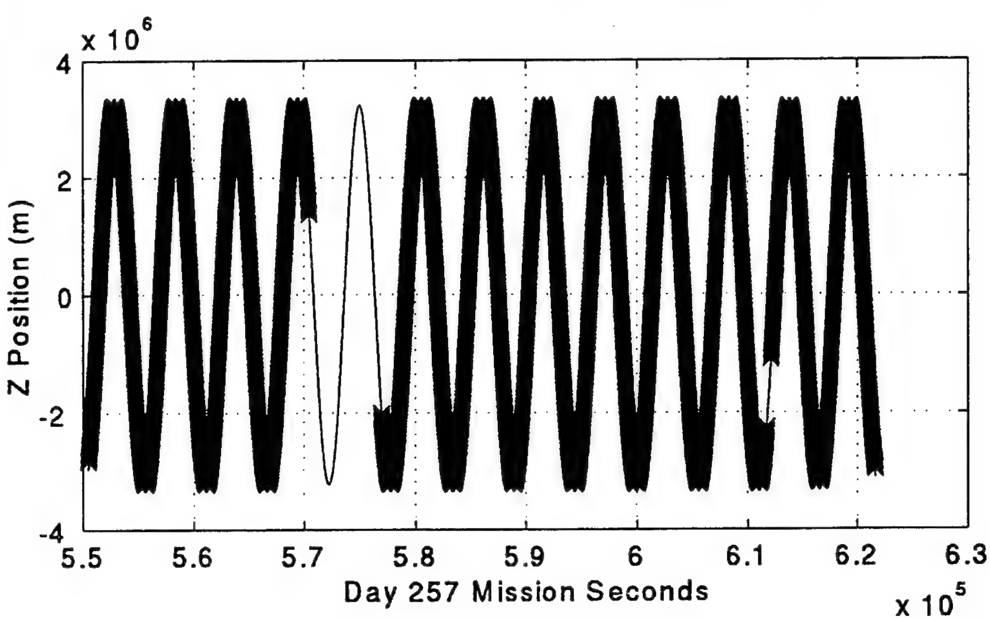

STS69propday7

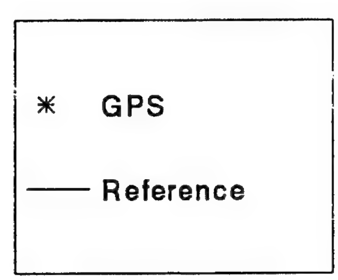

STS69propday7

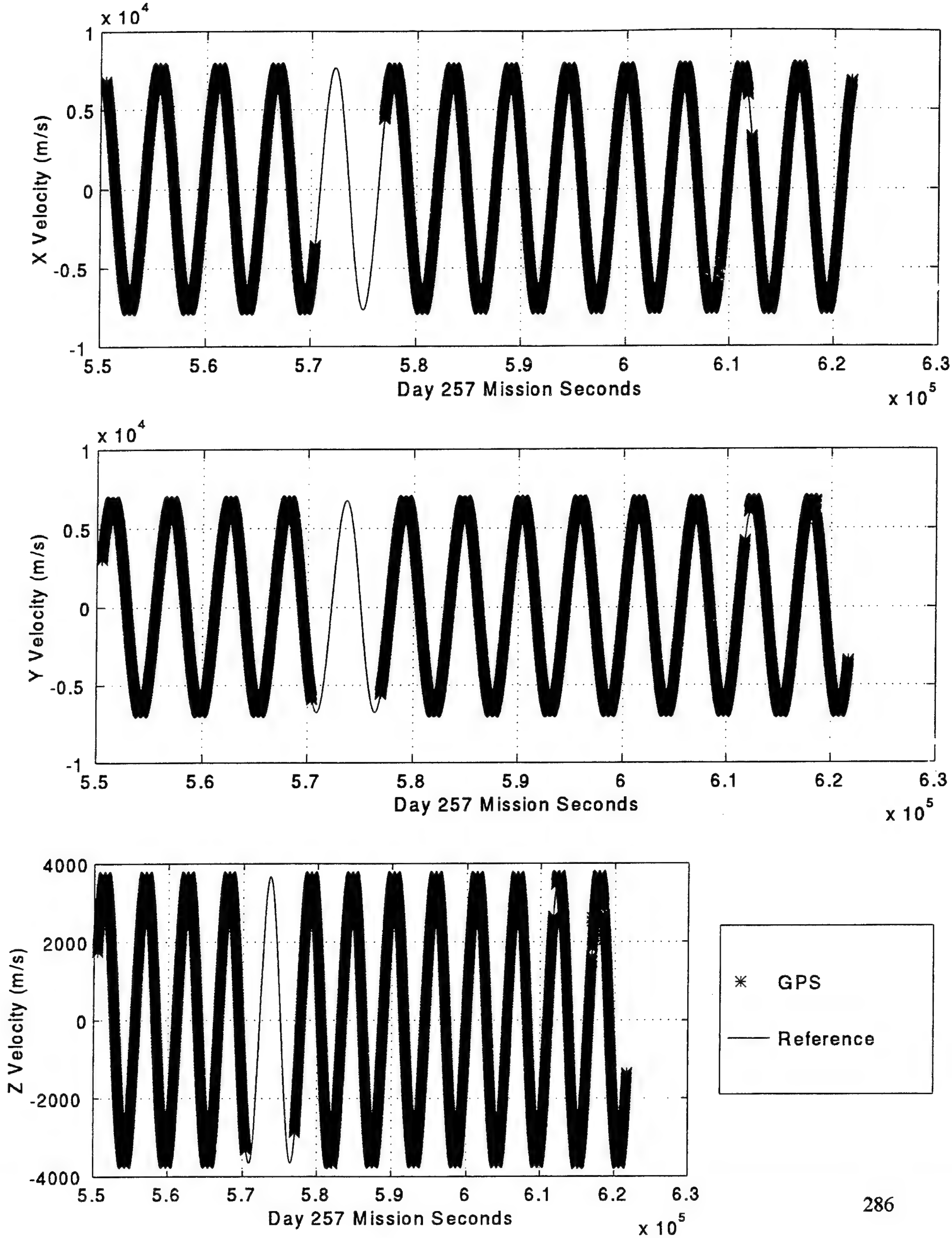
APPENDIX W. DAY 257 MATLAB PLOTS

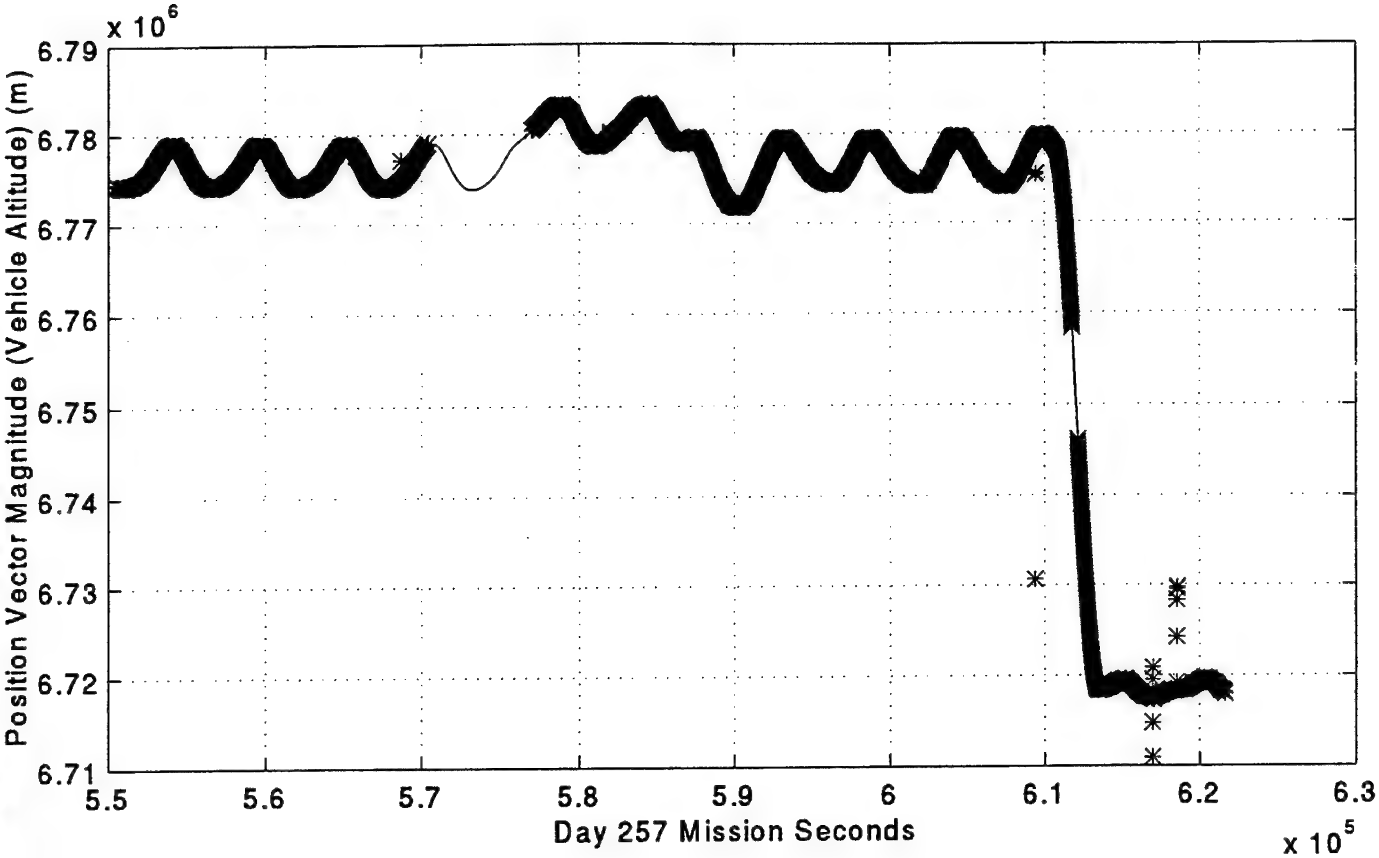

x 10^7
X Position (m)
Day 257 Mission Seconds
x 10^5

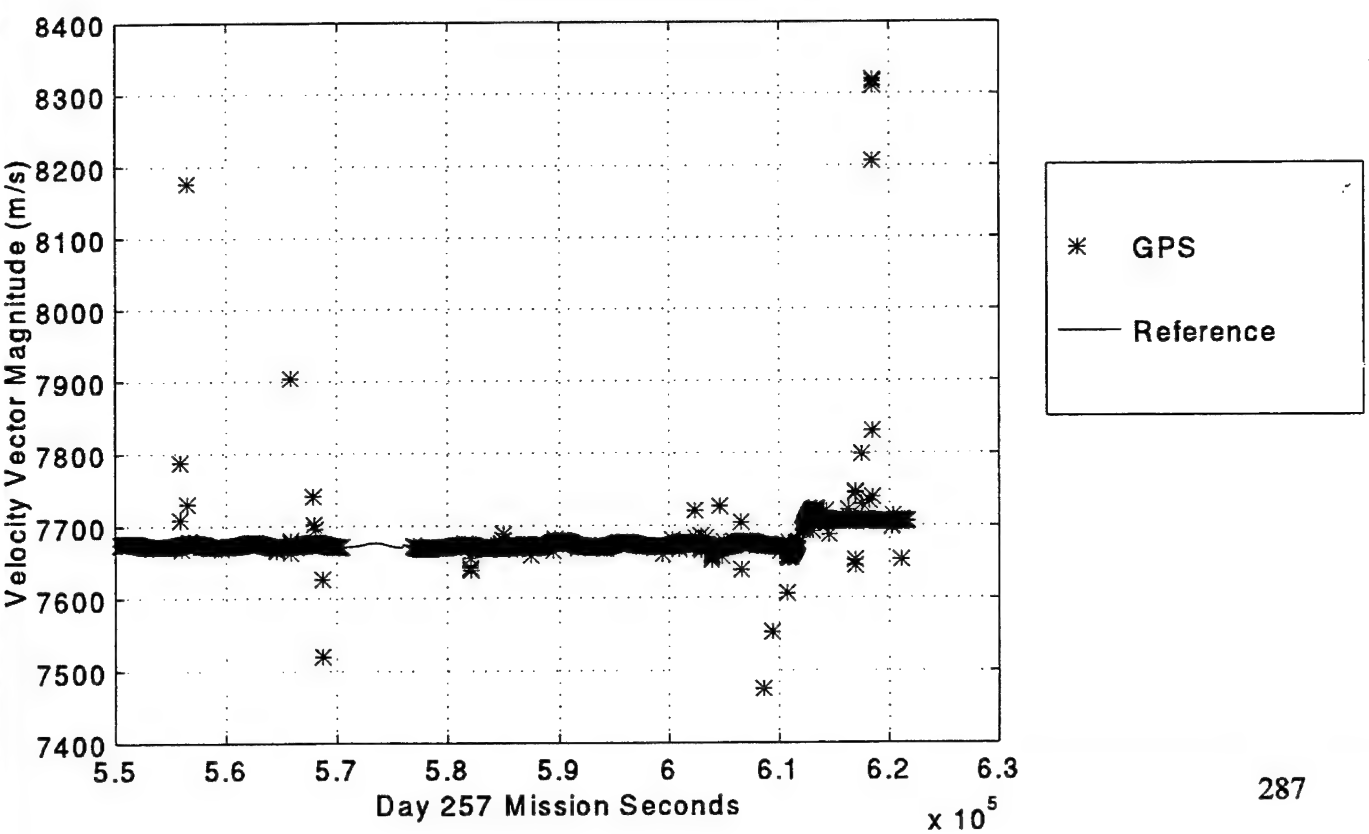

x 10^6
Y Position (m)
Day 257 Mission Seconds
x 10^5


x 10^6
Z Position (m)
Day 257 Mission Seconds
x 10^5

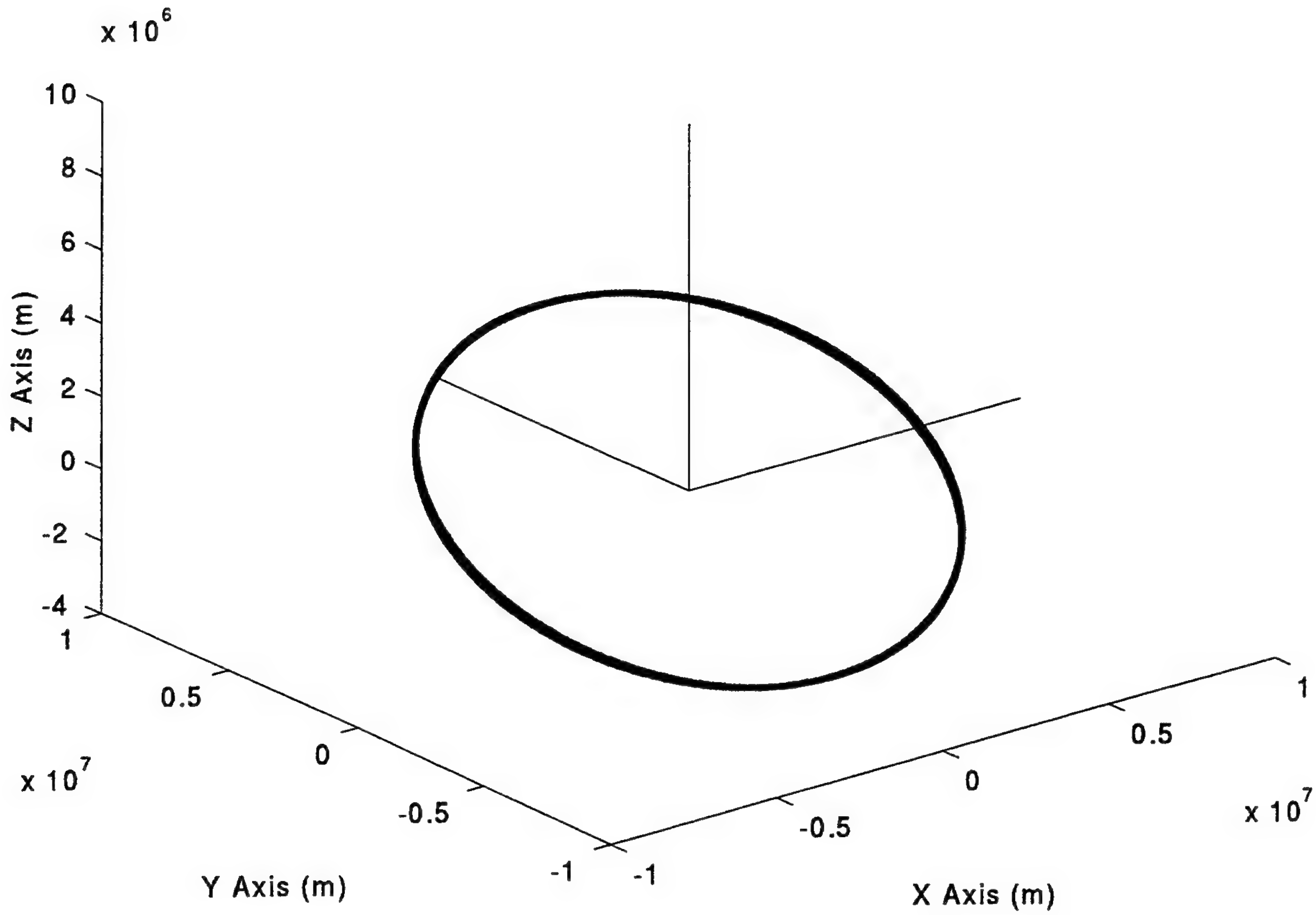

GPS
Reference


x 10^4
X Velocity (m/s)
1
0.5
0
-0.5
-1
5.5
5.6
5.7
5.8
5.9
6
6.1
6.2
6.3
Day 257 Mission Seconds
x 10^5
x 10^4
Y Velocity (m/s)
1
0.5
0
-0.5
-1
5.5
5.6
5.7
5.8
5.9
6
6.1
6.2
6.3
Day 257 Mission Seconds
x 10^5
Z Velocity (m/s)
4000
2000
0
-2000
-4000
5.5
5.6
5.7
5.8
5.9
6
6.1
6.2
6.3
Day 257 Mission Seconds
x 10^5
GPS
Reference

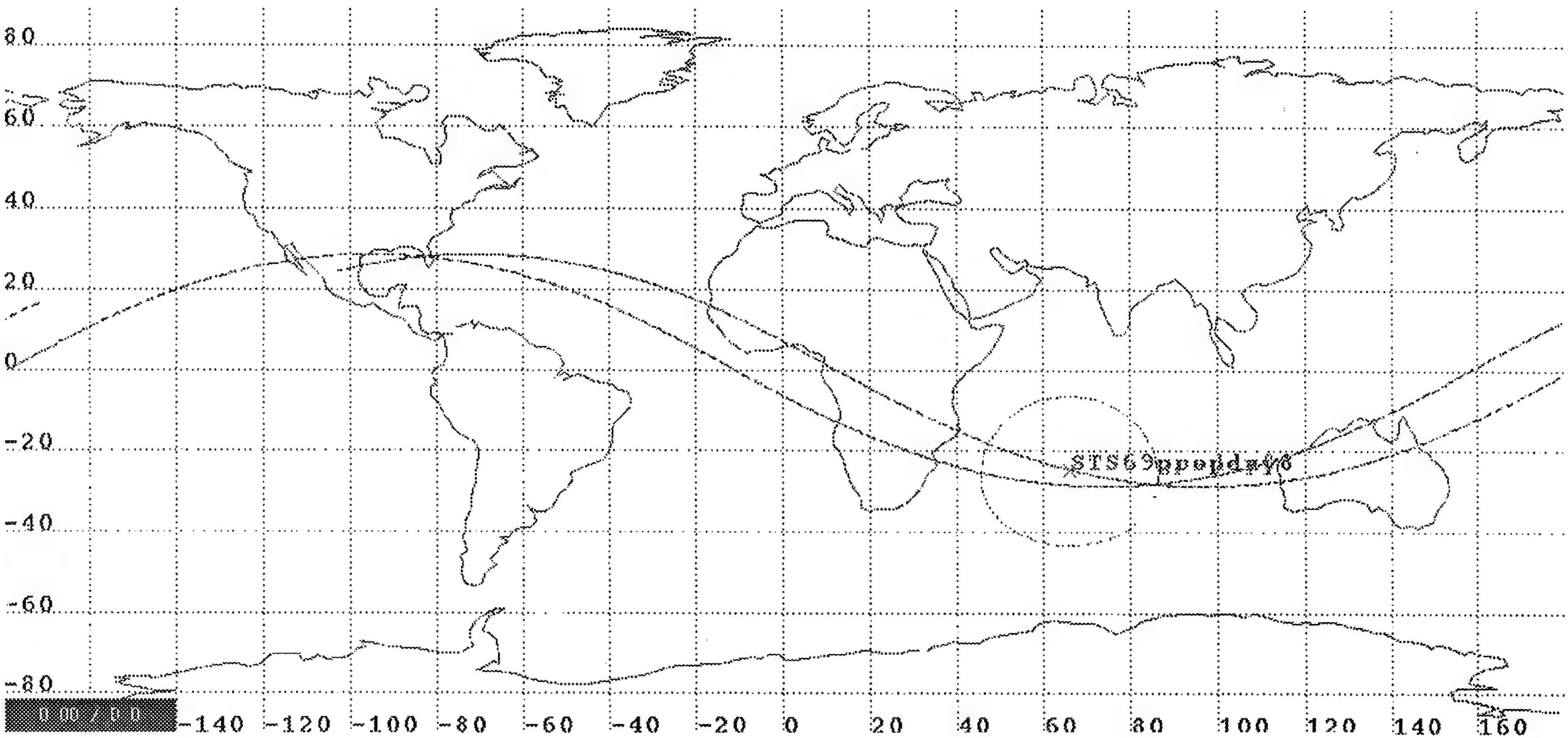

x 10^6
6.79
6.78
6.77
6.76
6.75
6.74
6.73
6.72
6.71
Position Vector Magnitude (Vehicle Altitude) (m)
5.5
5.6
5.7
5.8
5.9
6
6.1
6.2
6.3
Day 257 Mission Seconds
x 10^5

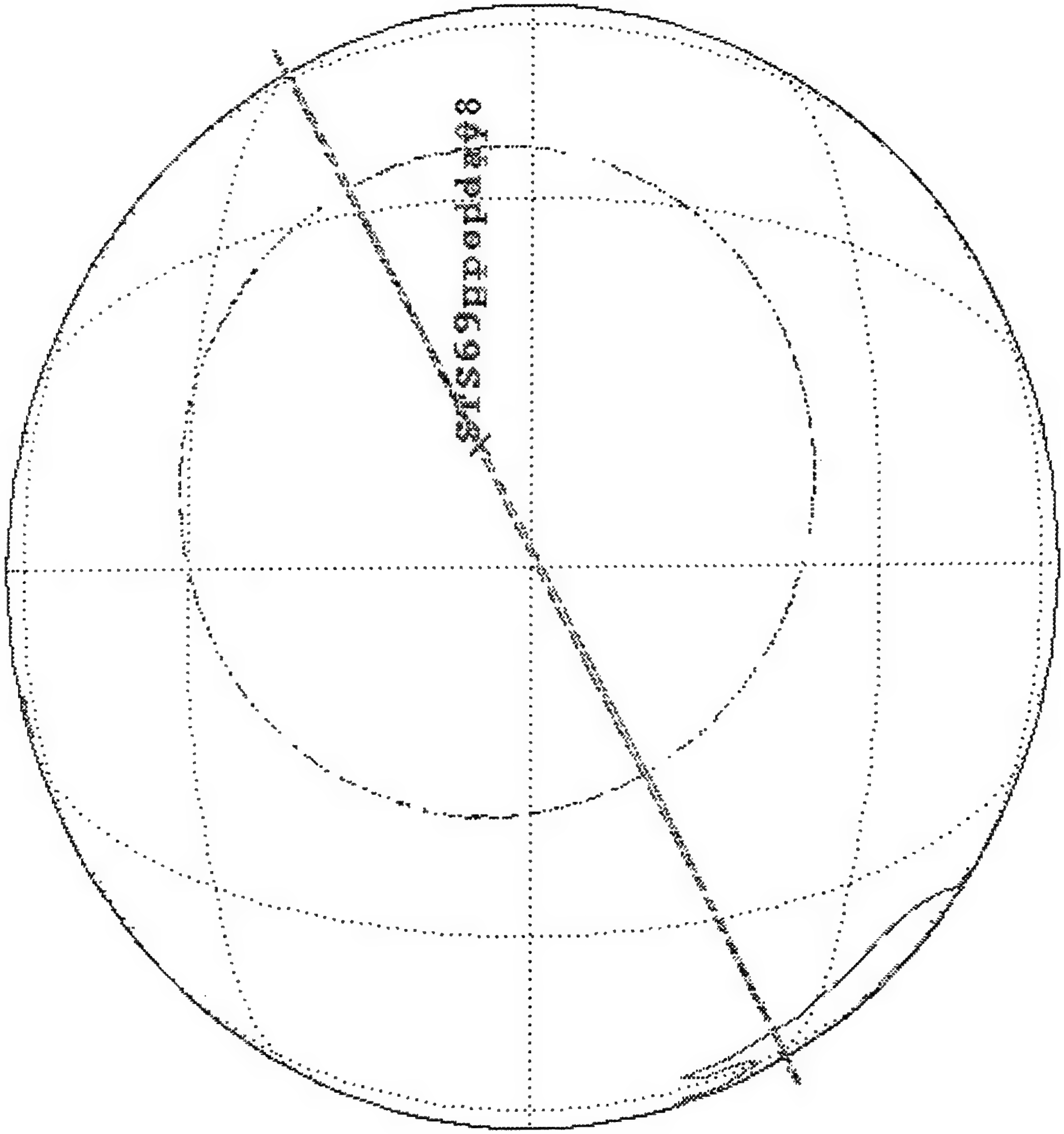

8400
8300
8200
8100
8000
7900
7800
7700
7600
7500
7400
Velocity Vector Magnitude (m/s)
5.5
5.6
5.7
5.8
5.9
6
6.1
6.2
6.3
Day 257 Mission Seconds
x 10^5
GPS
Reference

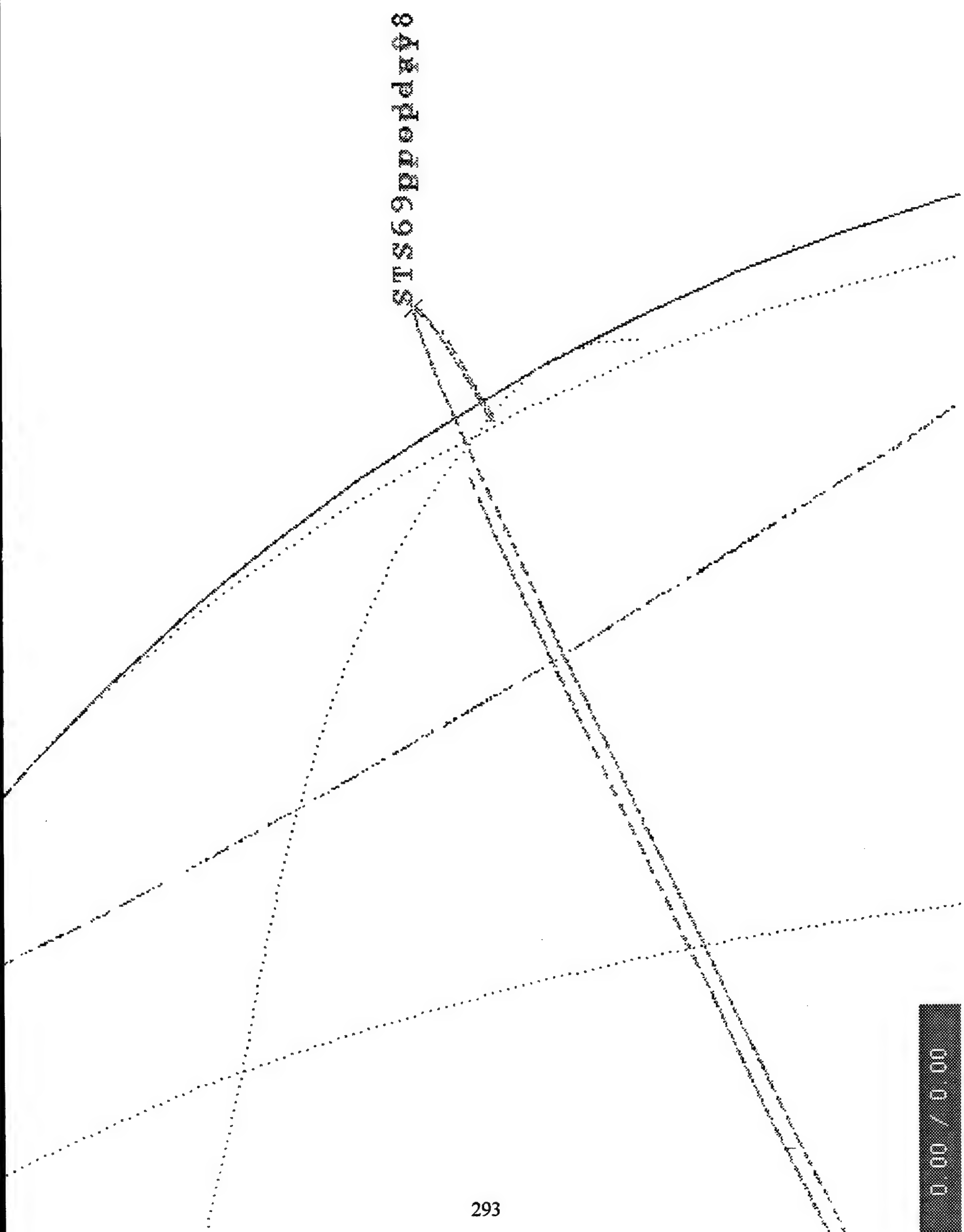
GPS Orbit for Day 257 in J2000 Coordinates

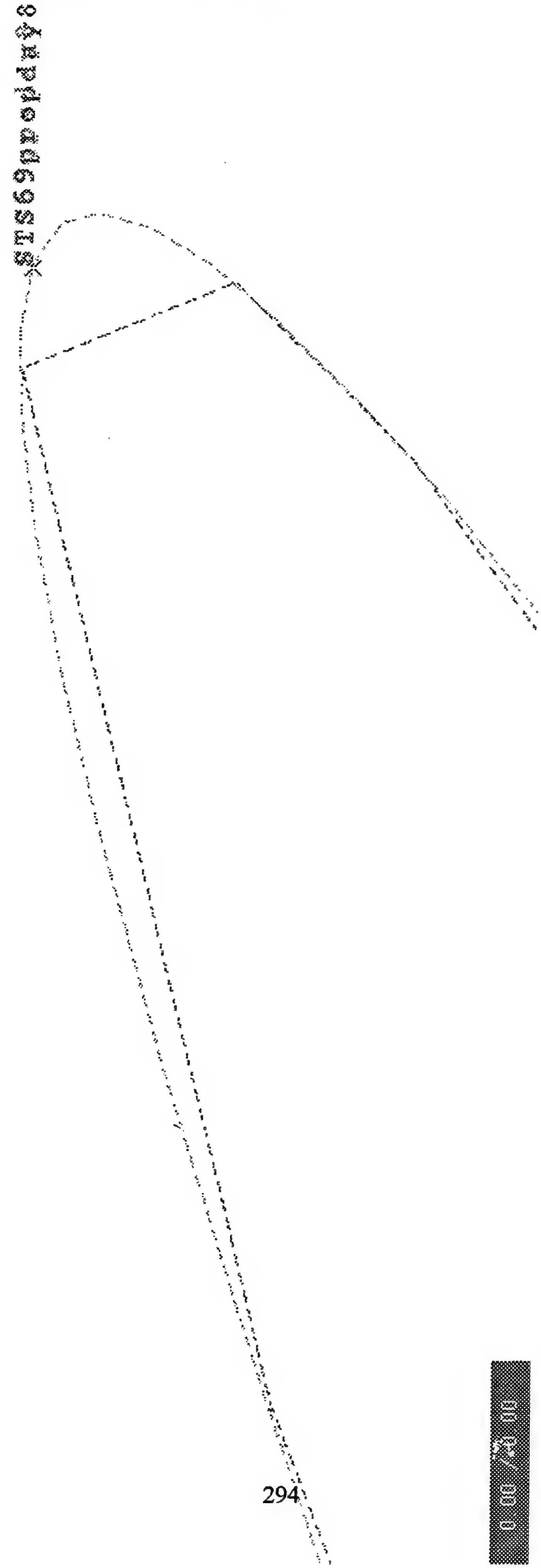


APPENDIX X. DAY 258 STK PLOTS

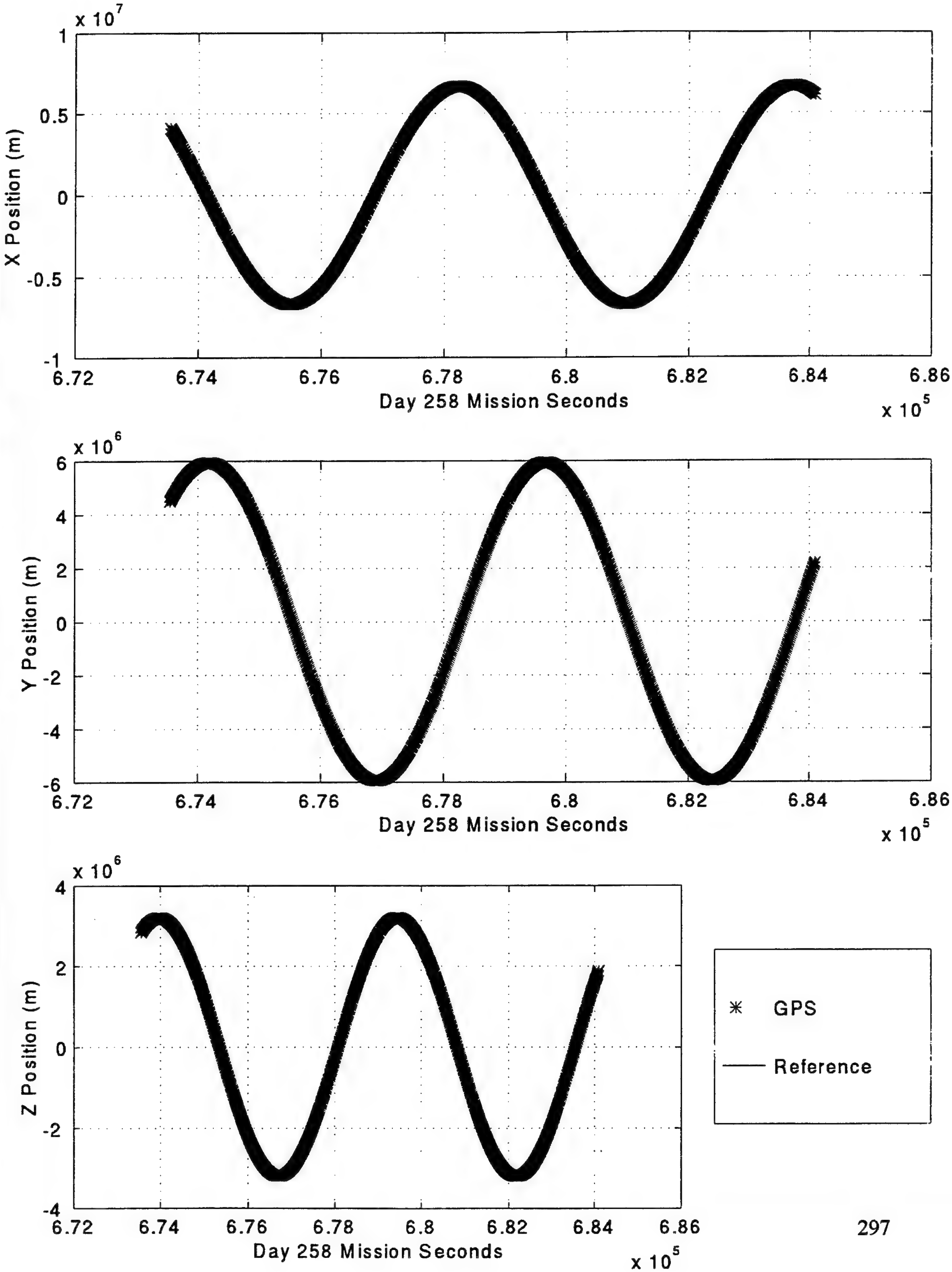

80
60
40
20
0
-20
-40
-60
-80
-140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160
STS69

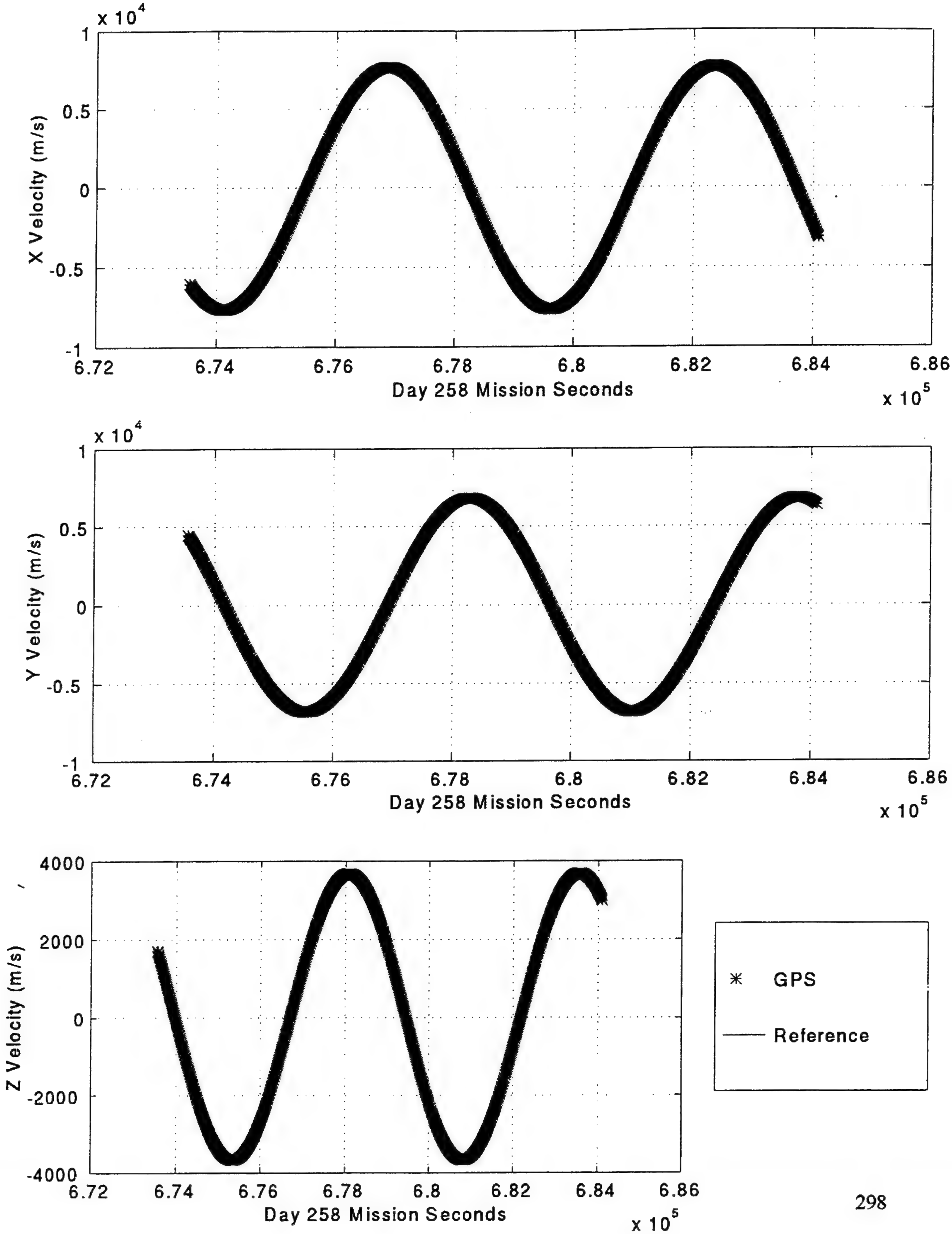

0.00 / 0.0

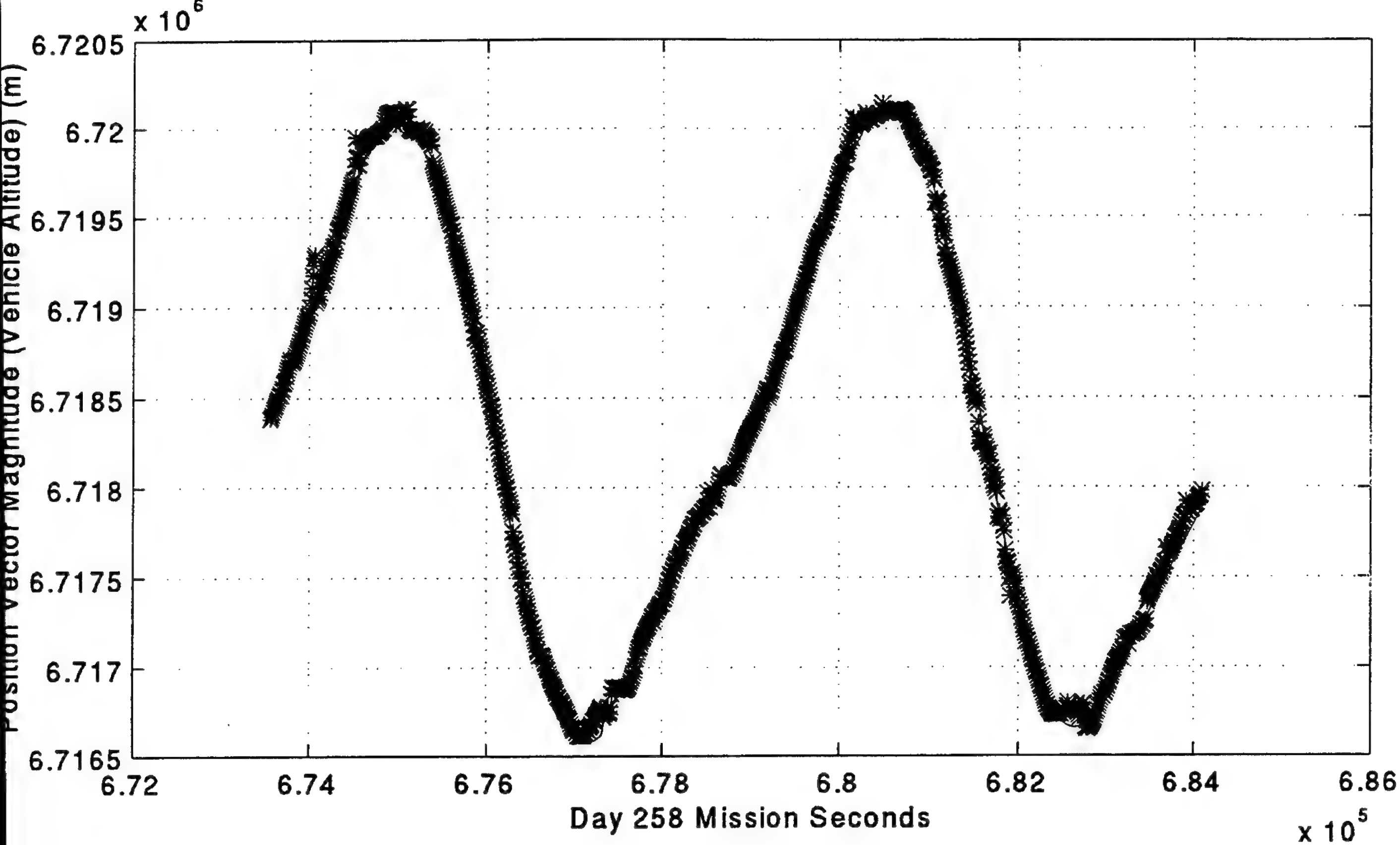


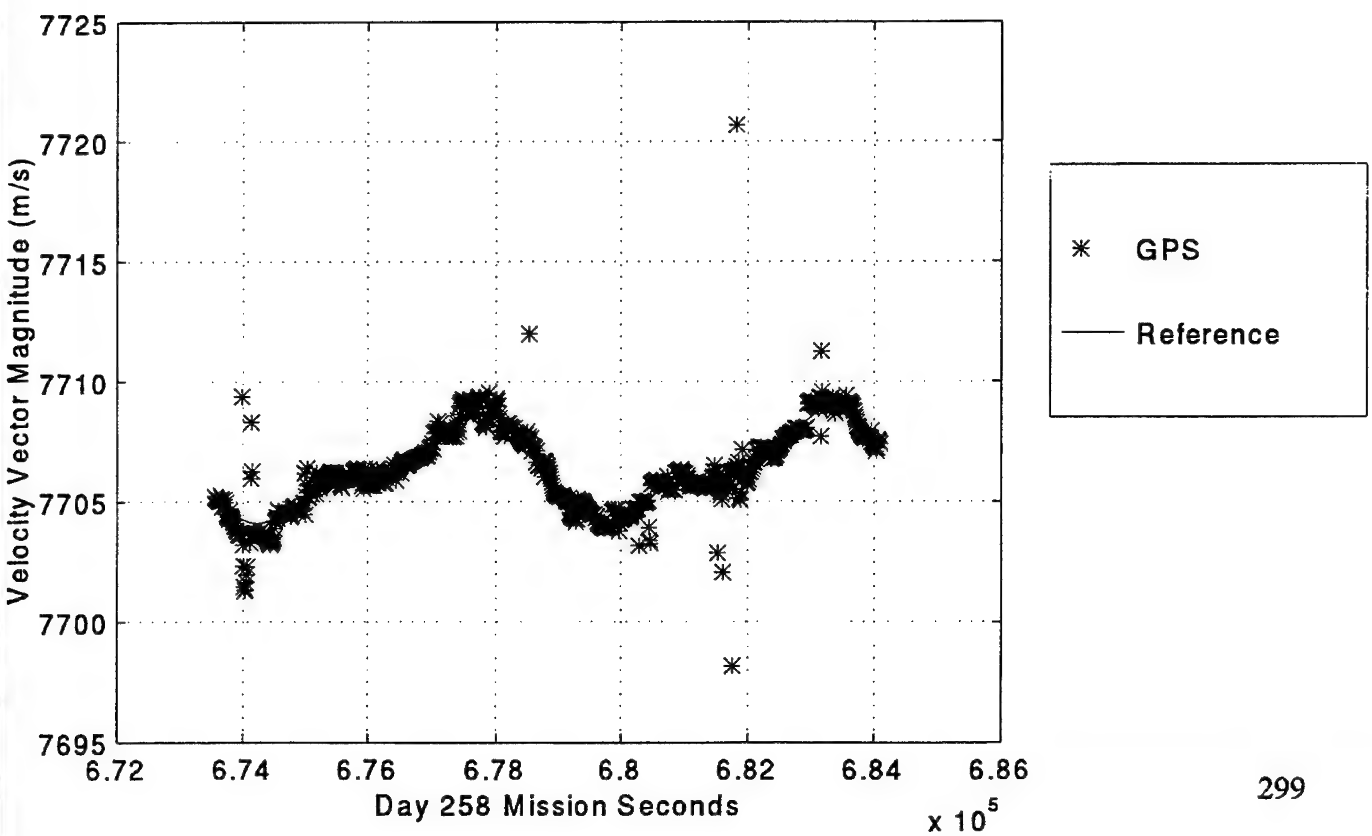


APPENDIX Y. DAY 258 MATLAB PLOTS

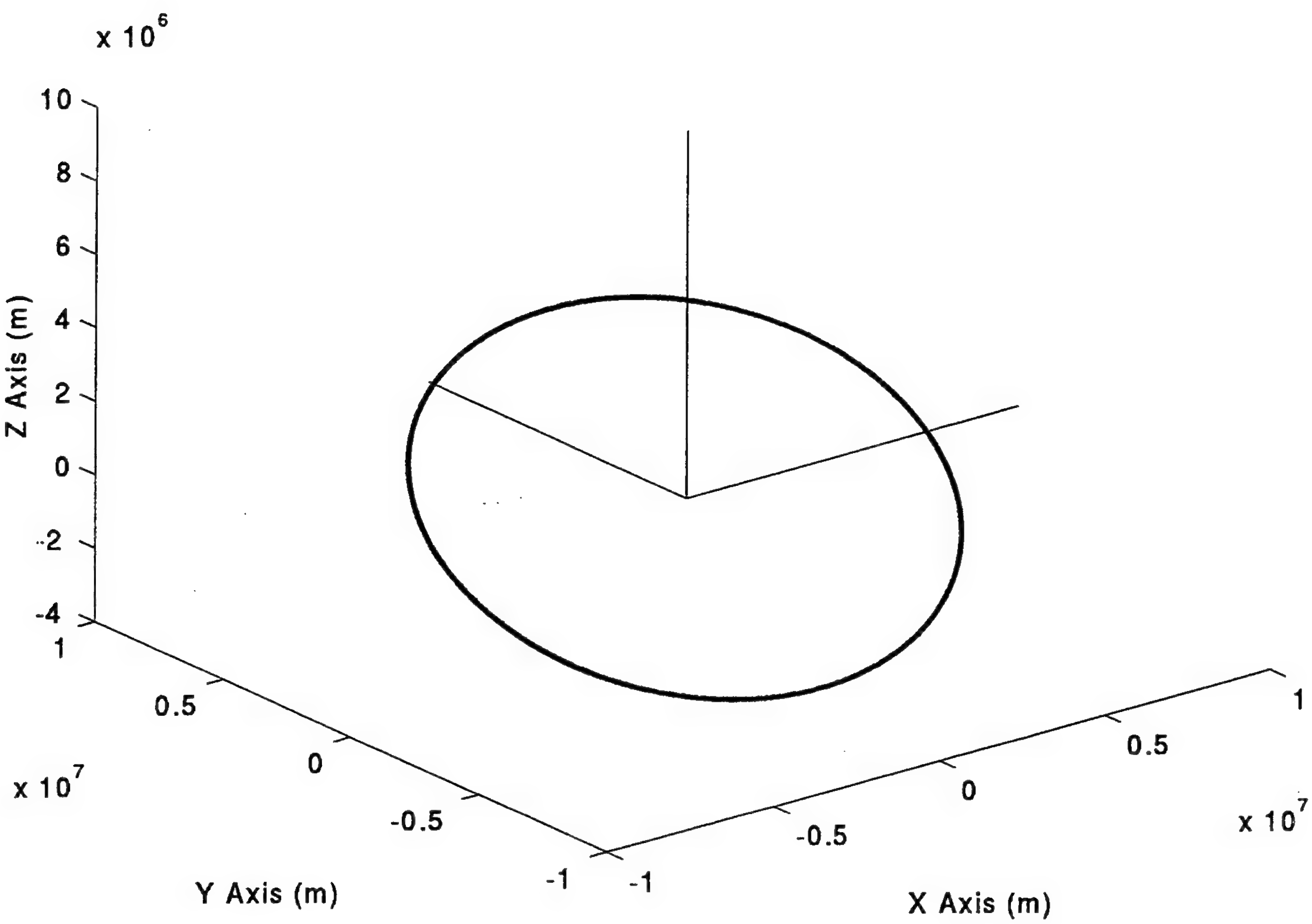

x 10^7
1
0.5
0
-0.5
-1
X Position (m)
6.72
6.74
6.76
6.78
6.8
6.82
6.84
6.86
Day 258 Mission Seconds
x 10^5
x 10^6
6
4
2
0
-2
-4
-6
Y Position (m)
6.72
6.74
6.76
6.78
6.8
6.82
6.84
6.86
Day 258 Mission Seconds
x 10^5
x 10^6
4
2
0
-2
-4
Z Position (m)
6.72
6.74
6.76
6.78
6.8
6.82
6.84
6.86
Day 258 Mission Seconds
x 10^5
GPS
Reference


x 10^4
X Velocity (m/s)
1
0.5
0
-0.5
-1
6.72
6.74
6.76
6.78
6.8
6.82
6.84
6.86
Day 258 Mission Seconds
x 10^5
x 10^4
Y Velocity (m/s)
1
0.5
0
-0.5
-1
6.72
6.74
6.76
6.78
6.8
6.82
6.84
6.86
Day 258 Mission Seconds
x 10^5
Z Velocity (m/s)
4000
2000
0
-2000
-4000
6.72
6.74
6.76
6.78
6.8
6.82
6.84
6.86
Day 258 Mission Seconds
x 10^5
* GPS
Reference

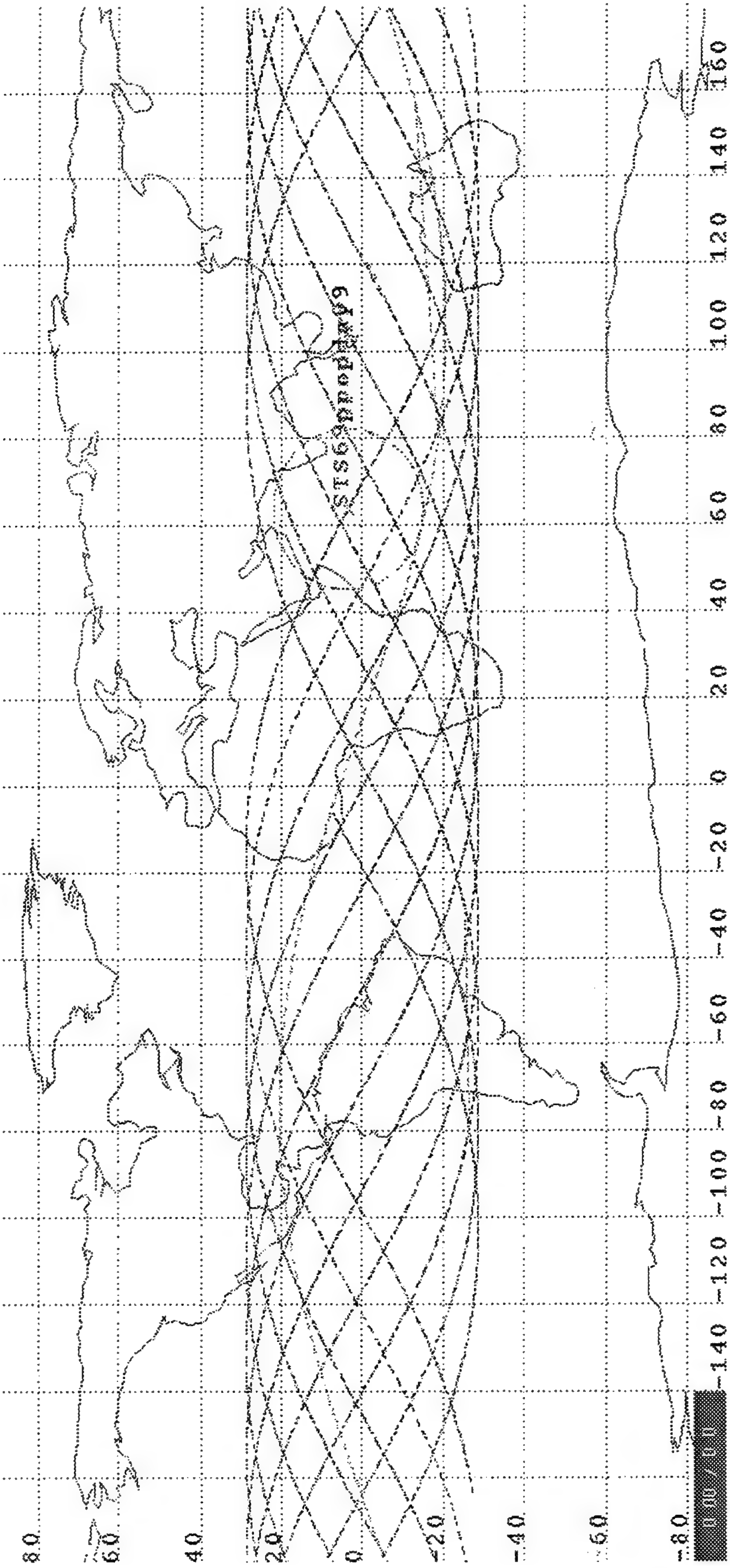

x 10^6
6.7205
6.72
6.7195
6.719
6.7185
6.718
6.7175
6.717
6.7165
Position Vector Magnitude (Vehicle Altitude) (m)
6.72
6.74
6.76
6.78
6.8
6.82
6.84
6.86
Day 258 Mission Seconds
x 10^5

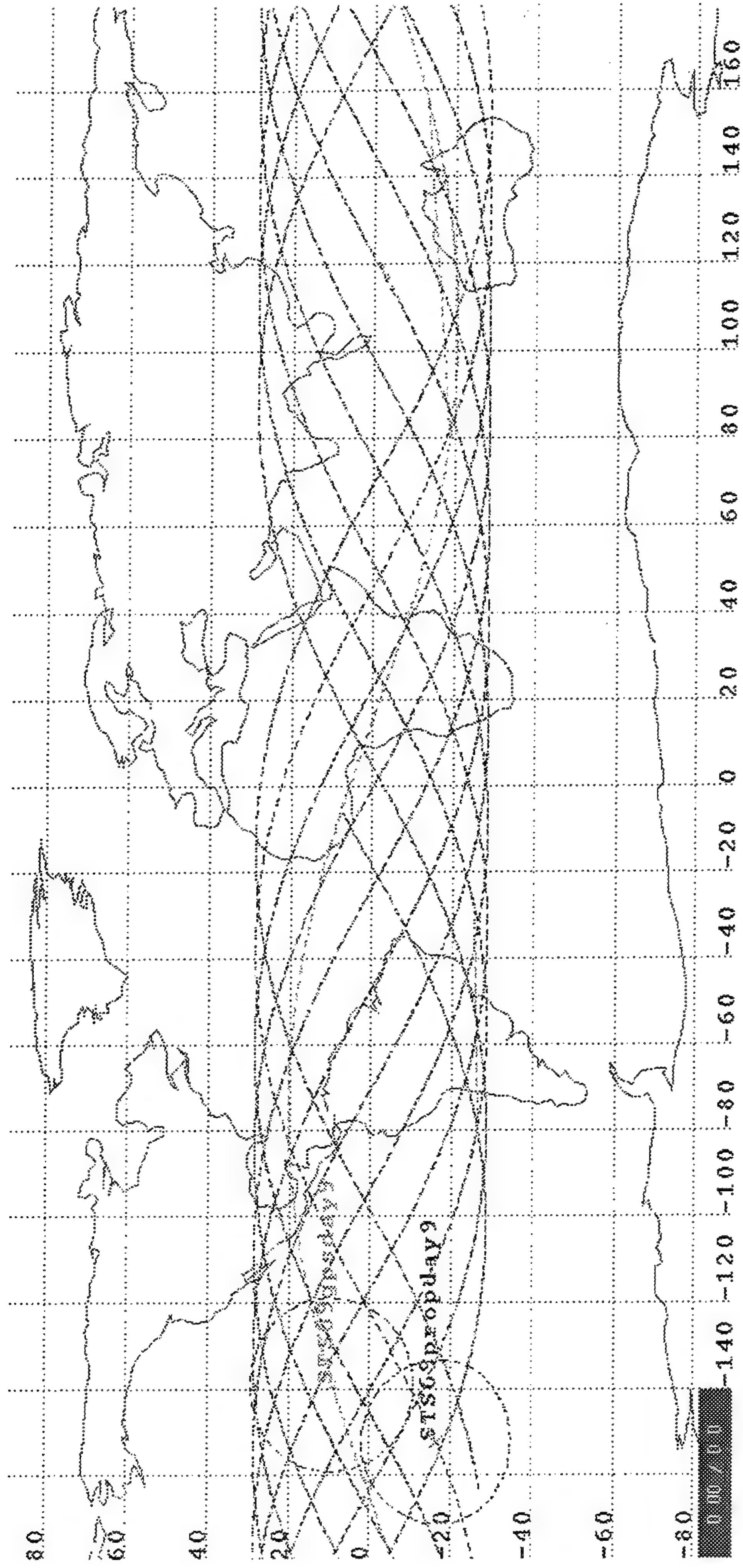

7725
7720
7715
7710
7705
7700
7695
Velocity Vector Magnitude (m/s)
6.72
6.74
6.76
6.78
6.8
6.82
6.84
6.86
Day 258 Mission Seconds
x 10^5
GPS
Reference

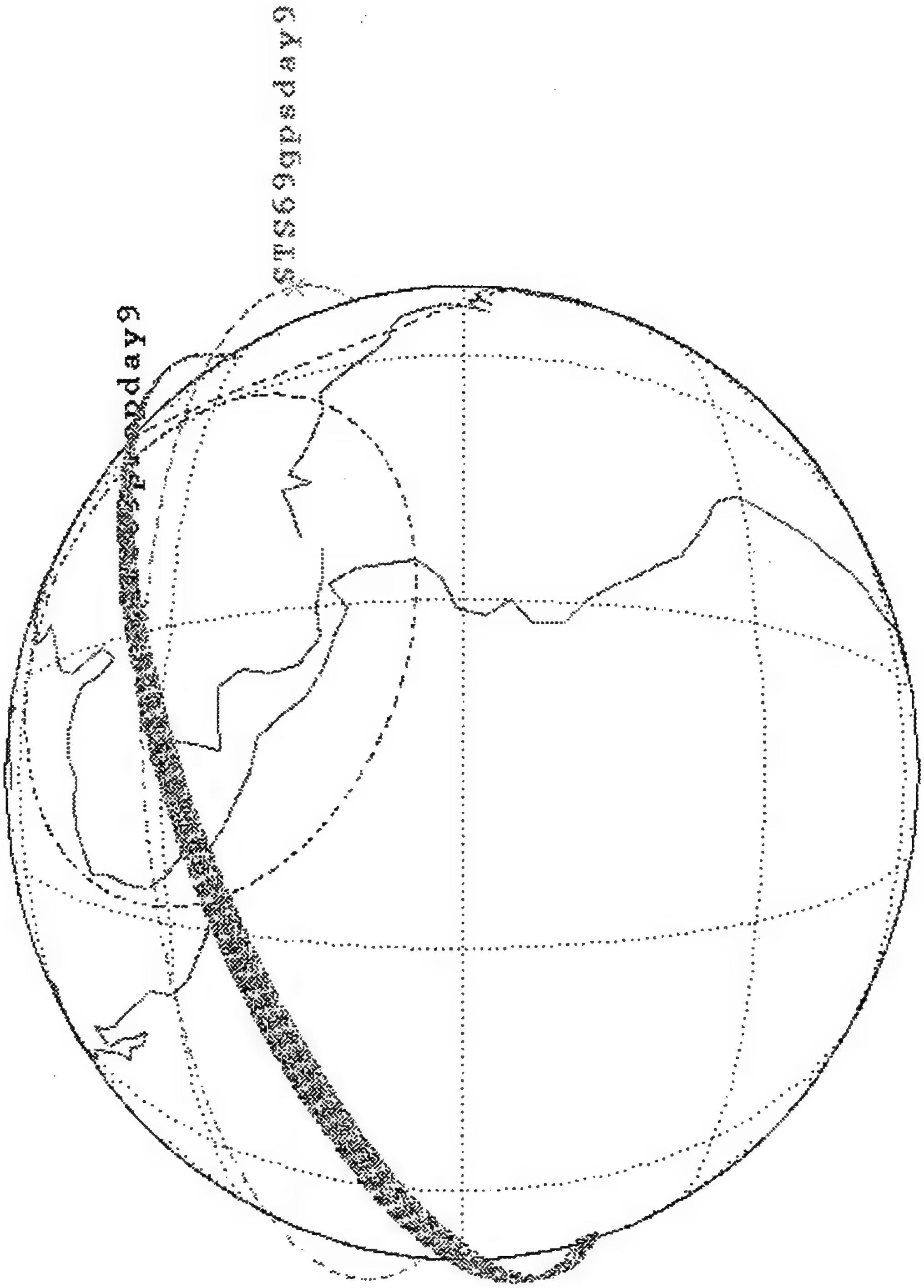
GPS Orbit for Day 258 in J2000 Coordinates

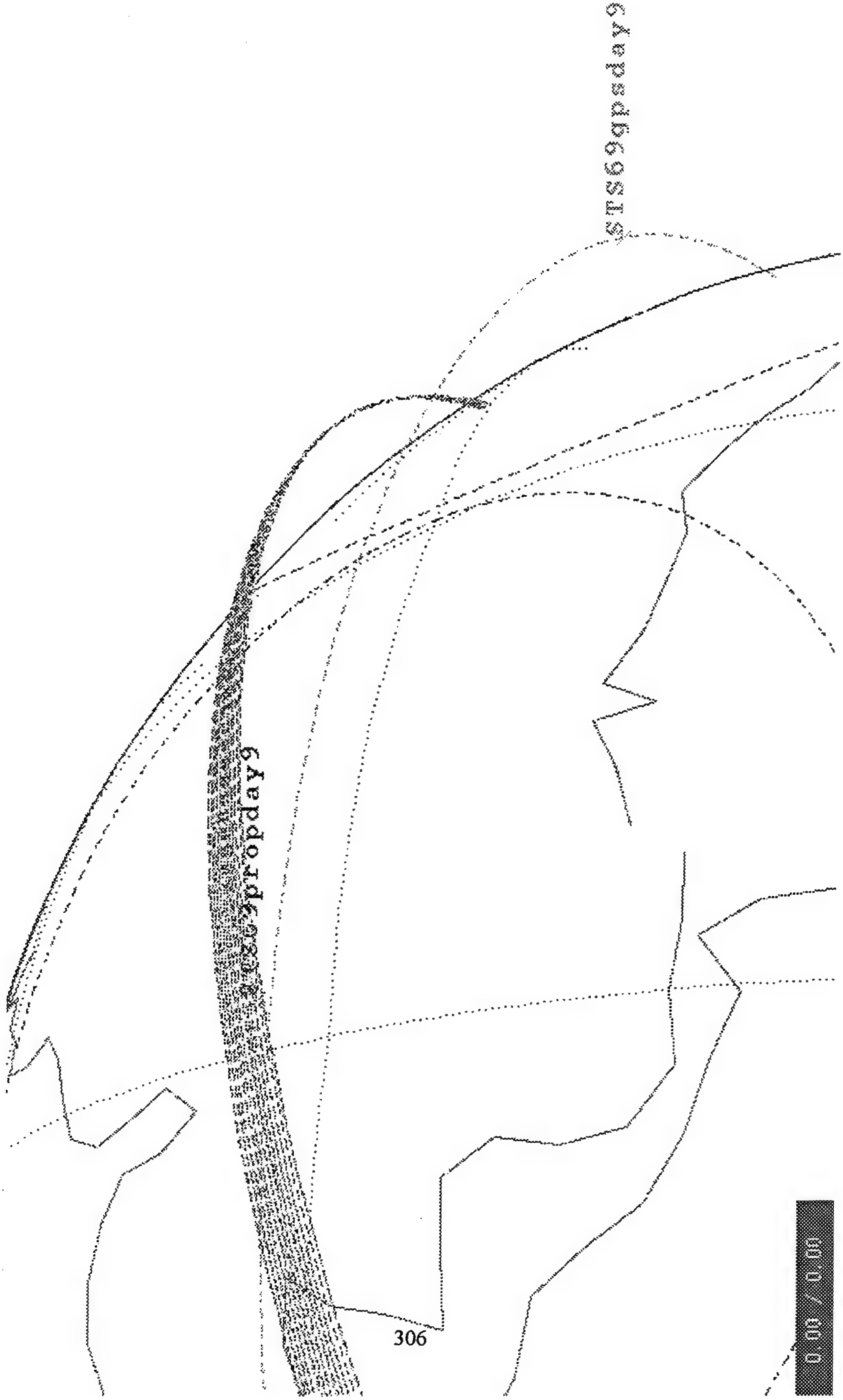


APPENDIX Z. DAY 259 STK PLOTS

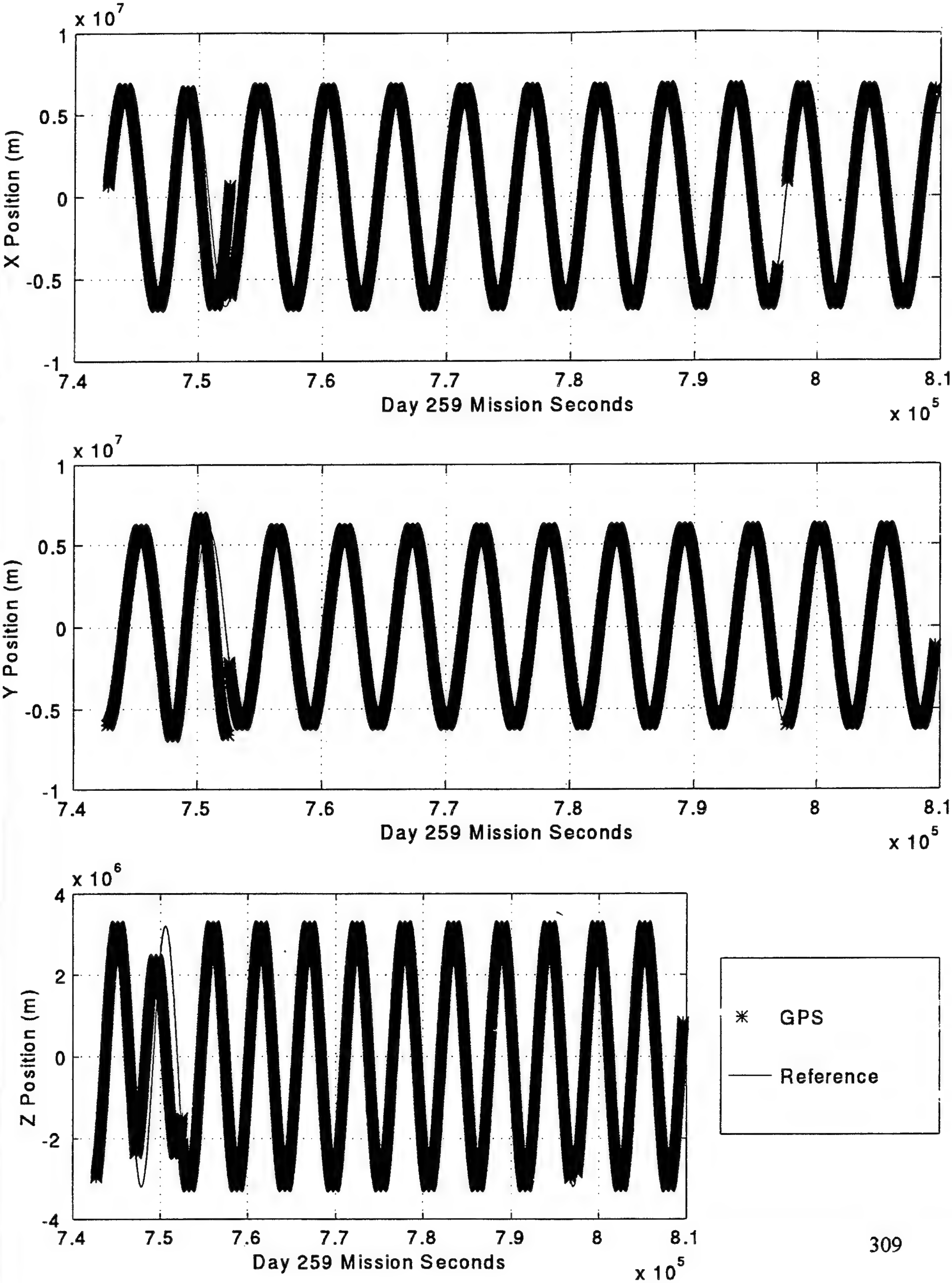

80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

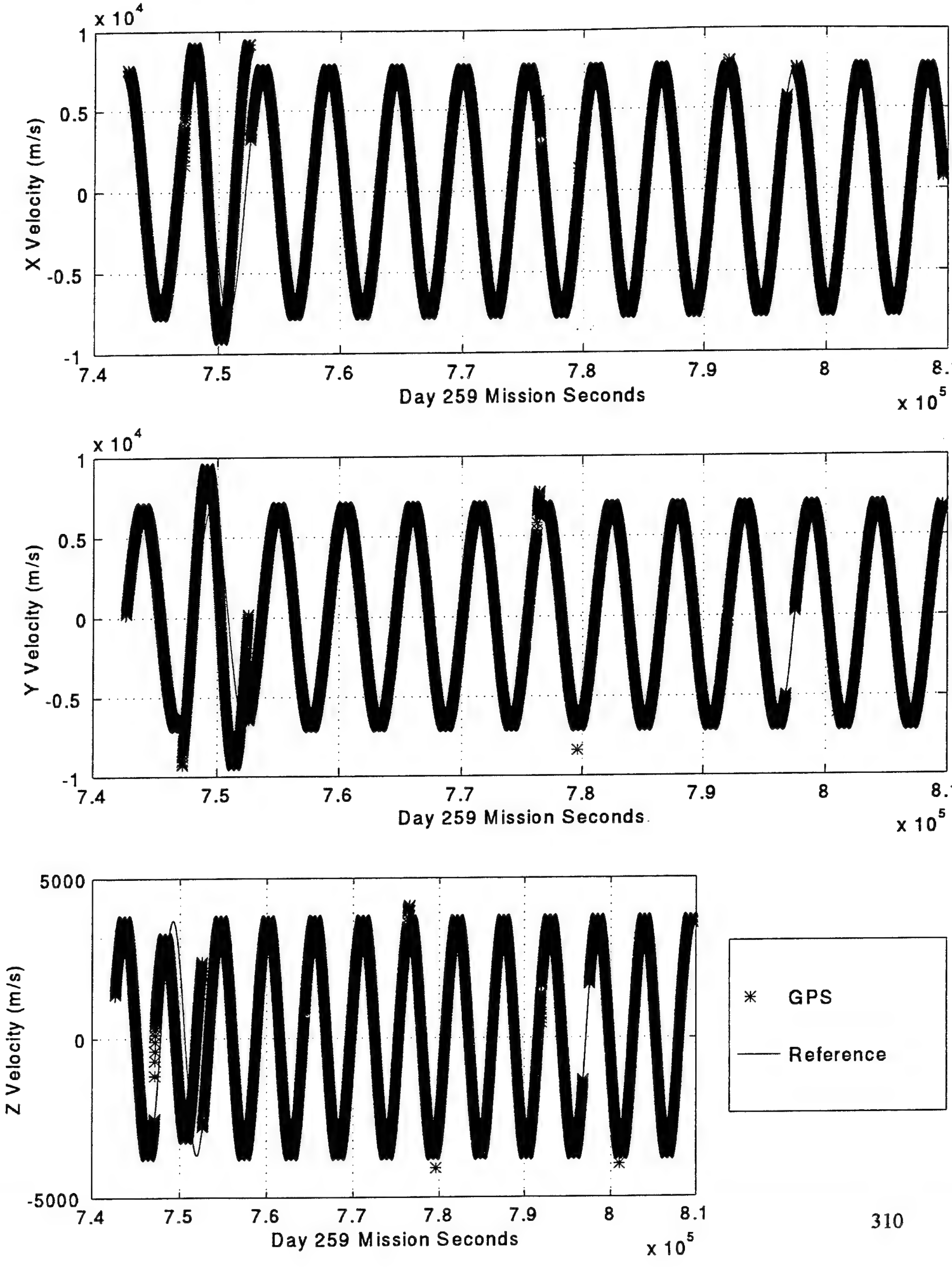

80
60
40
20
0
-20
-40
-60
-80
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140

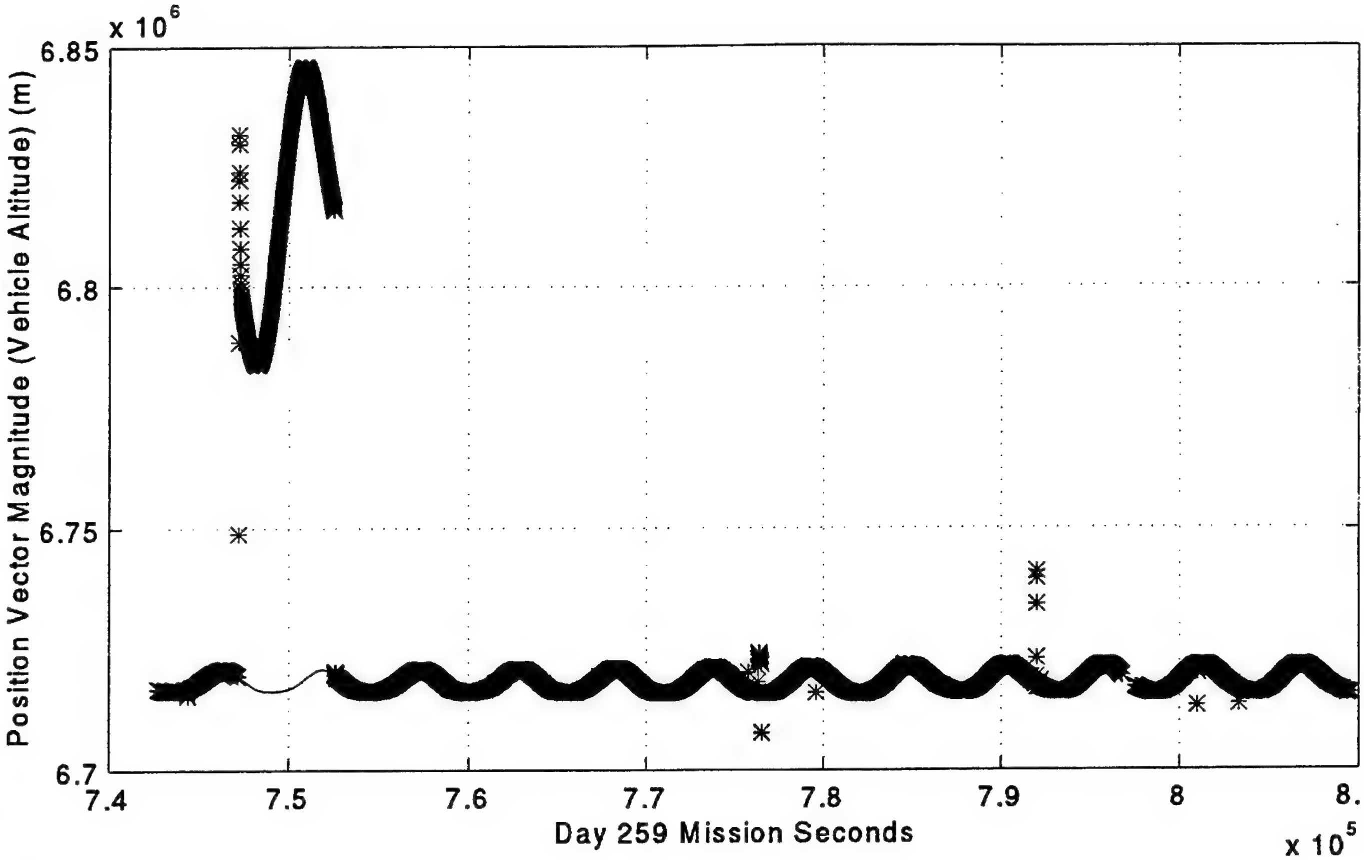

STS69gpsday9

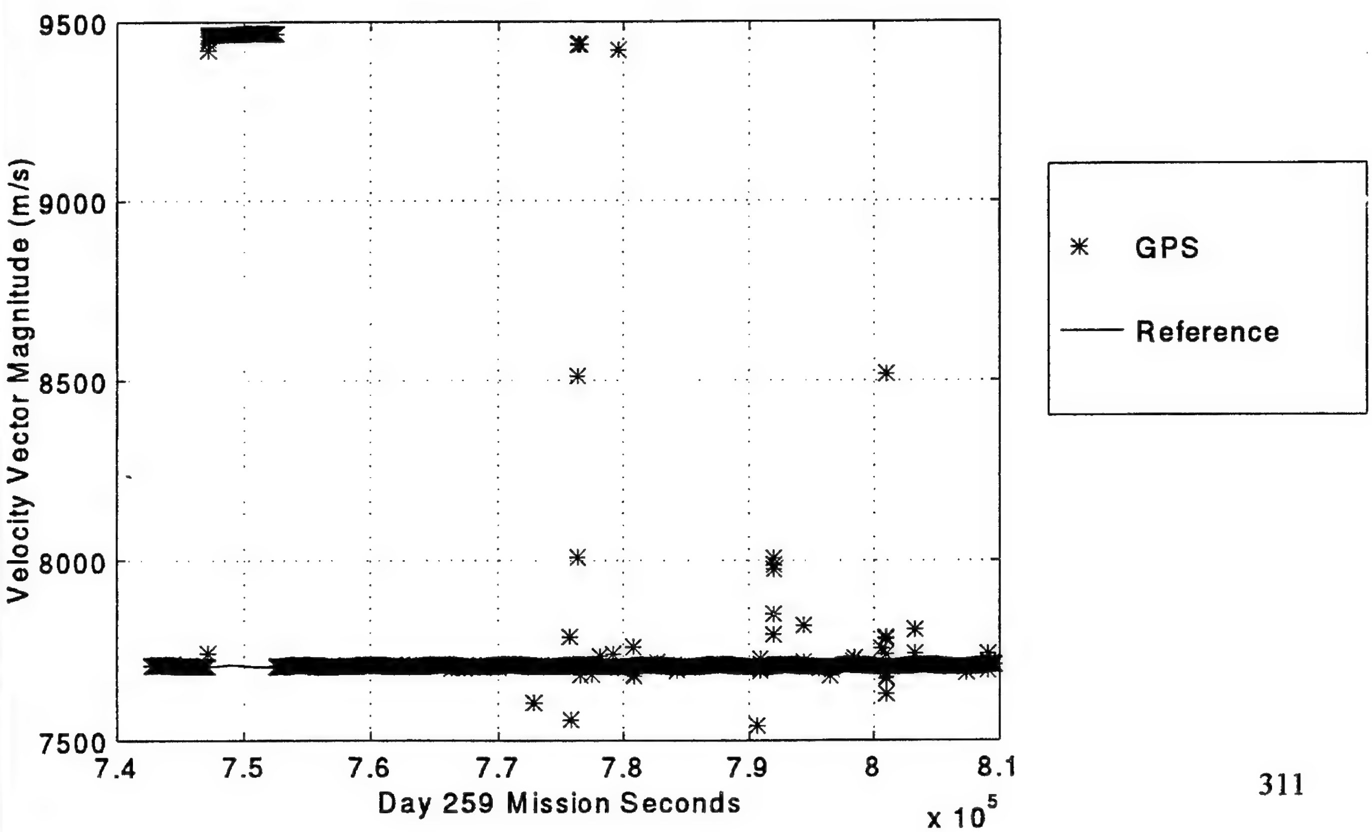

STS69gpsday9
0 nm / 0 nm

APPENDIX AA. DAY 259 MATLAB PLOTS

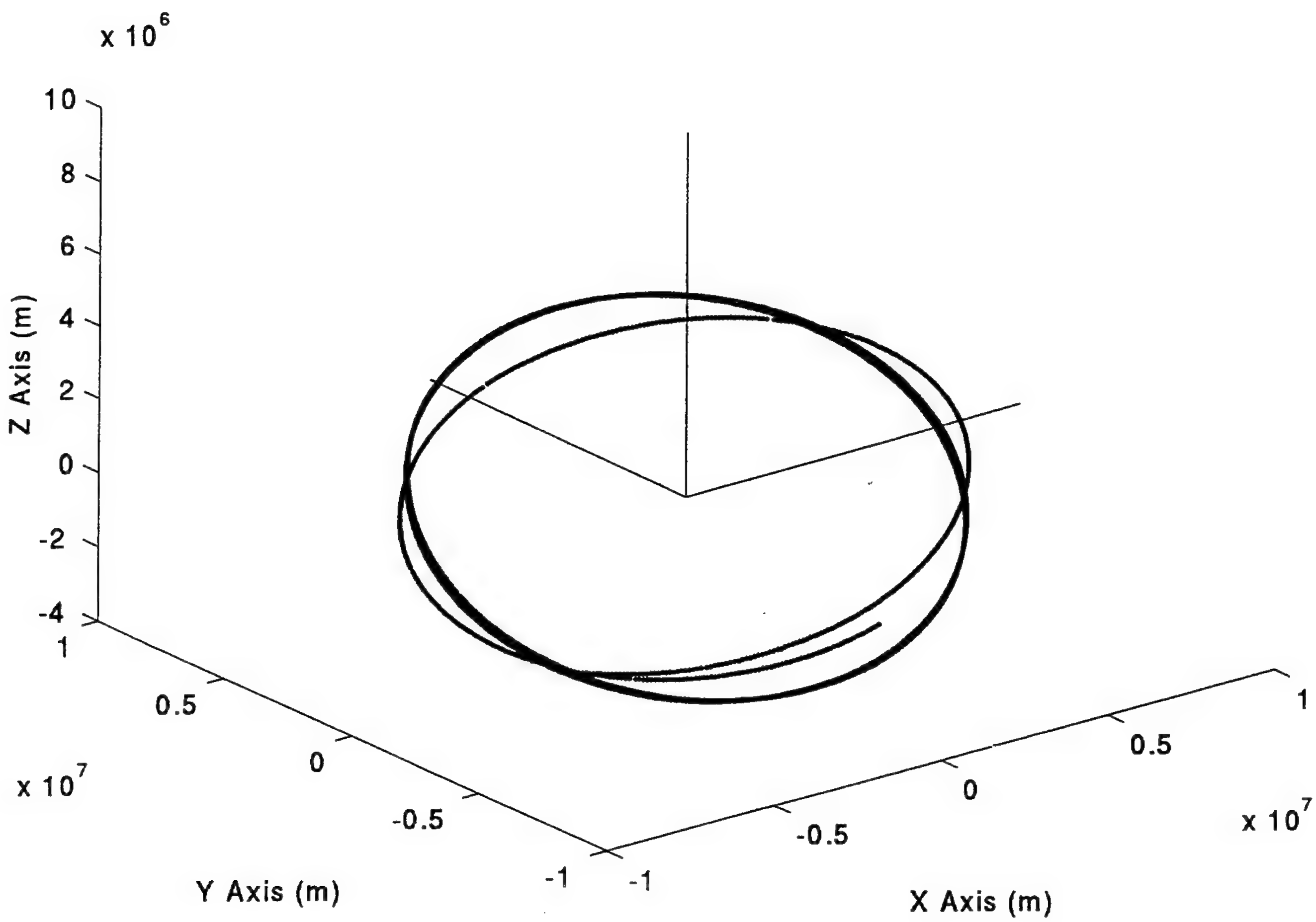

x 10^7
X Position (m)
1
0.5
0
-0.5
-1
7.4
7.5
7.6
7.7
7.8
7.9
8
8.1
Day 259 Mission Seconds
x 10^5
x 10^7
Y Position (m)
1
0.5
0
-0.5
-1
7.4
7.5
7.6
7.7
7.8
7.9
8
8.1
Day 259 Mission Seconds
x 10^5
x 10^6
Z Position (m)
4
2
0
-2
-4
7.4
7.5
7.6
7.7
7.8
7.9
8
8.1
Day 259 Mission Seconds
x 10^5
GPS
Reference


x 10^4
X Velocity (m/s)
Day 259 Mission Seconds
x 10^5
Y Velocity (m/s)
Day 259 Mission Seconds
Z Velocity (m/s)
Day 259 Mission Seconds
GPS
Reference

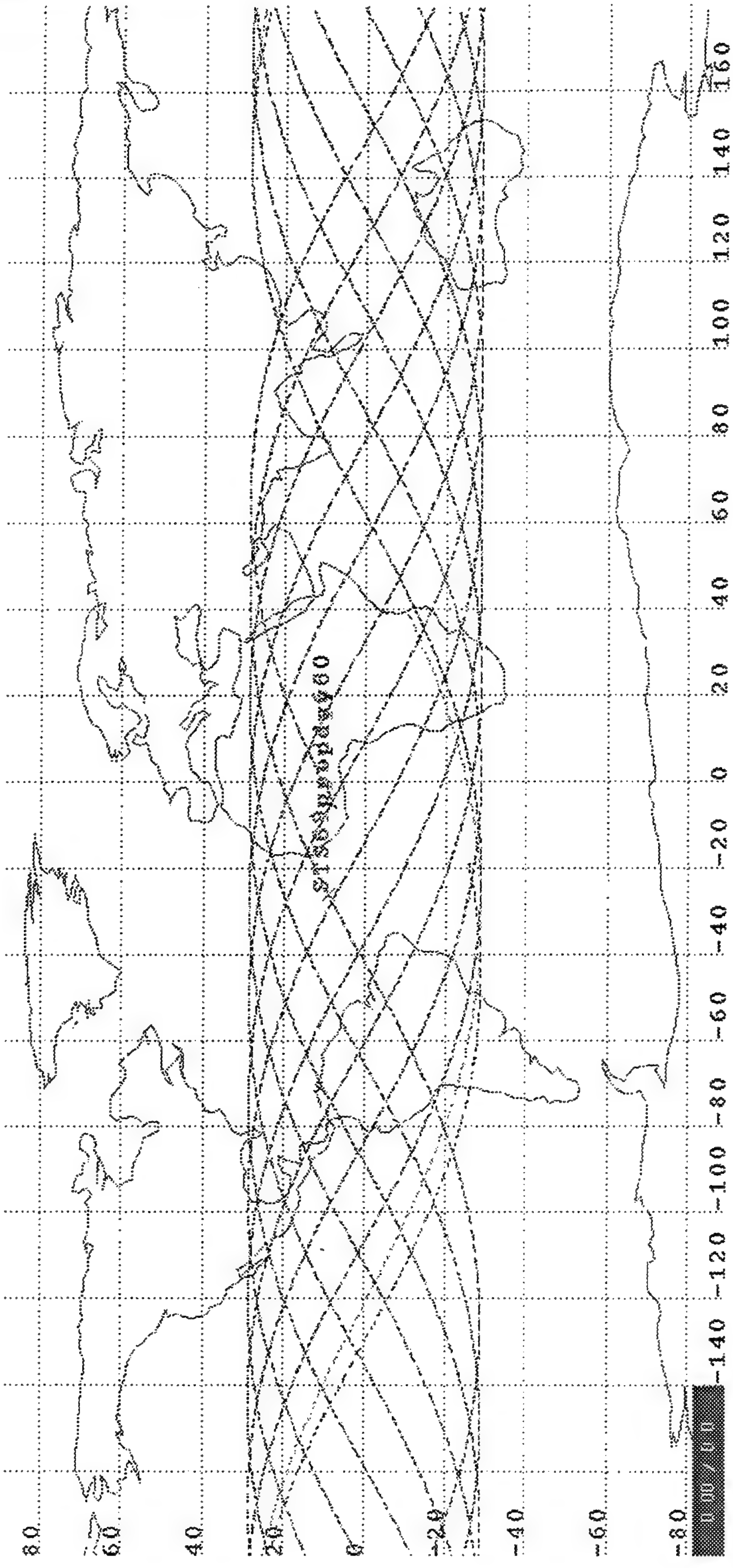

x 10^6
6.85
6.8
6.75
6.7
Position Vector Magnitude (Vehicle Altitude) (m)
7.4
7.5
7.6
7.7
7.8
7.9
8
8.1
Day 259 Mission Seconds
x 10^5

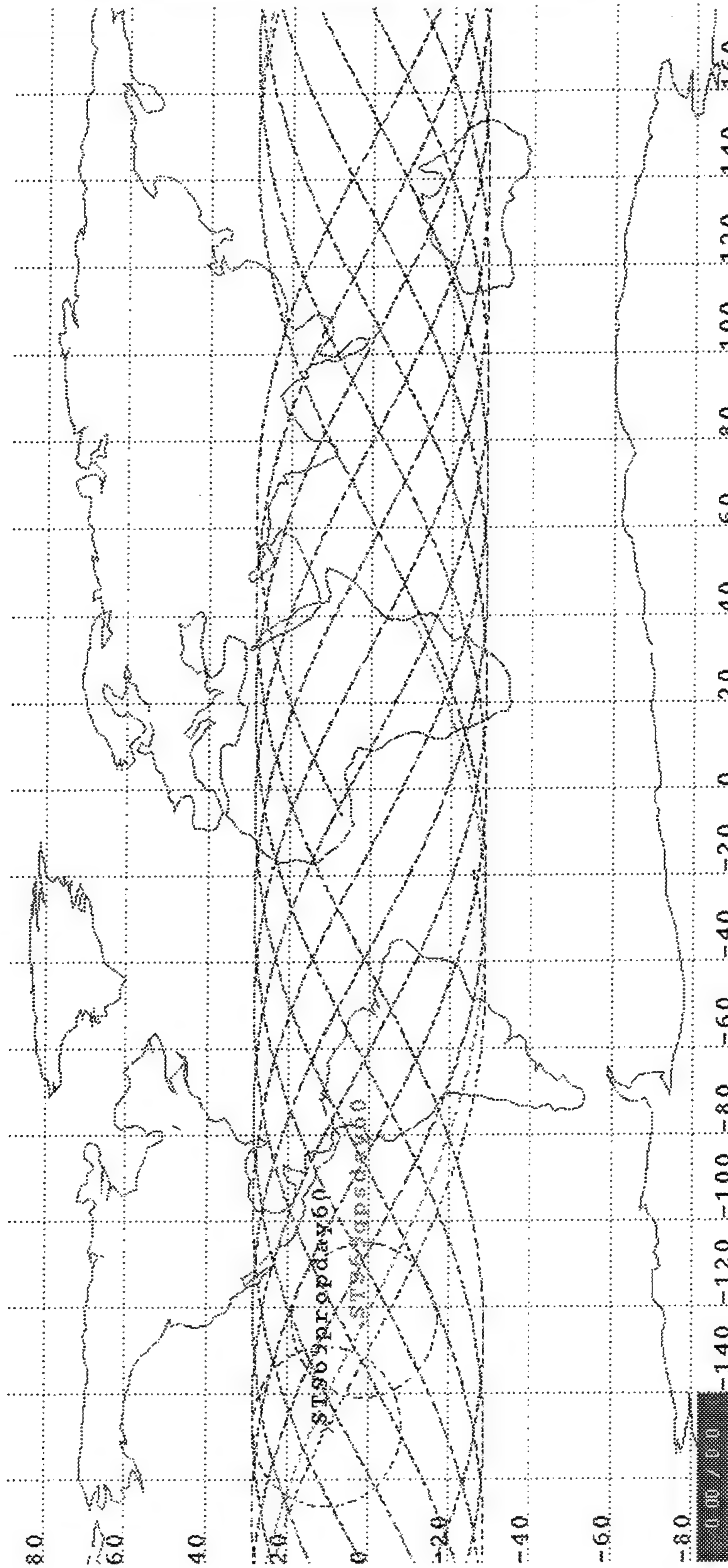

9500
9000
8500
8000
7500
Velocity Vector Magnitude (m/s)
7.4
7.5
7.6
7.7
7.8
7.9
8
8.1
Day 259 Mission Seconds
x 10^5
GPS
Reference

GPS Orbit for Day 259 in J2000 Coordinates

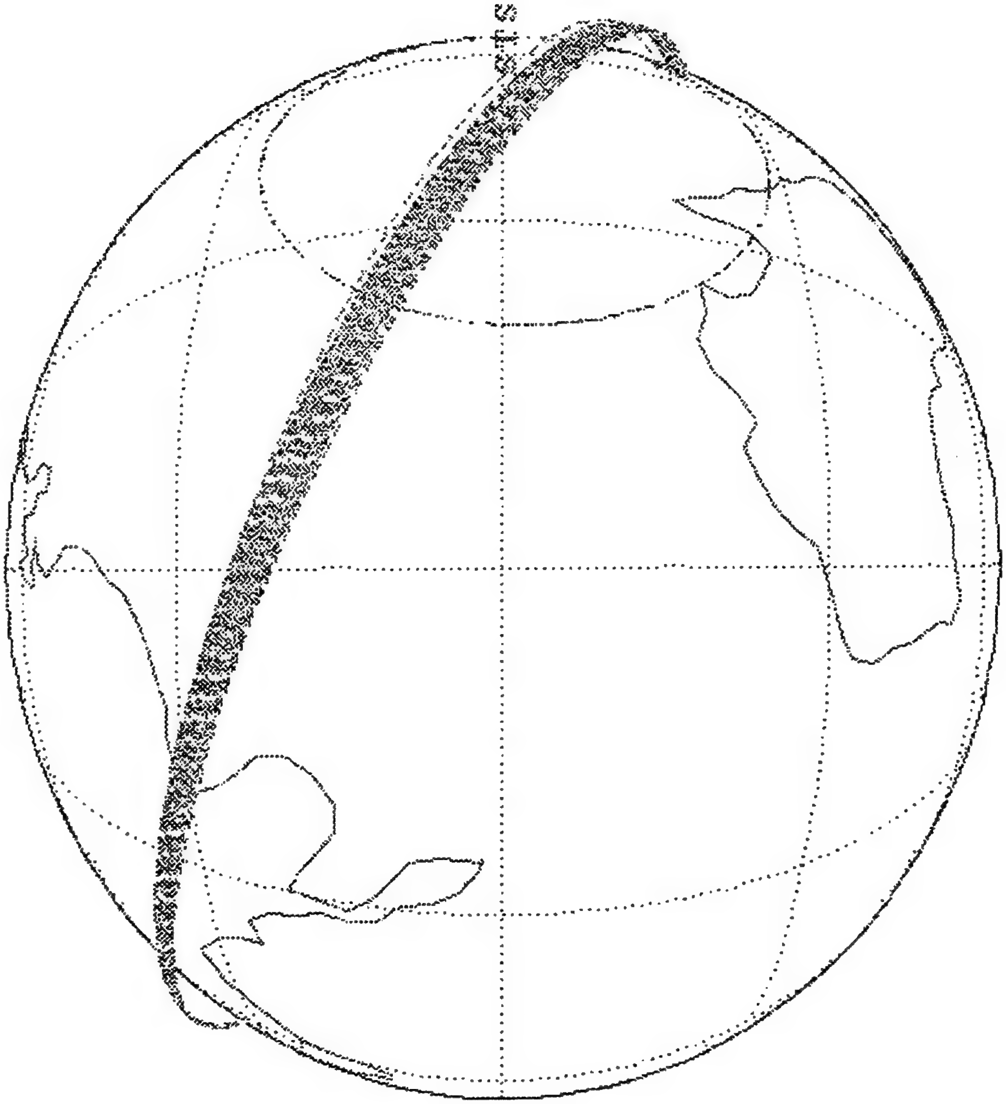


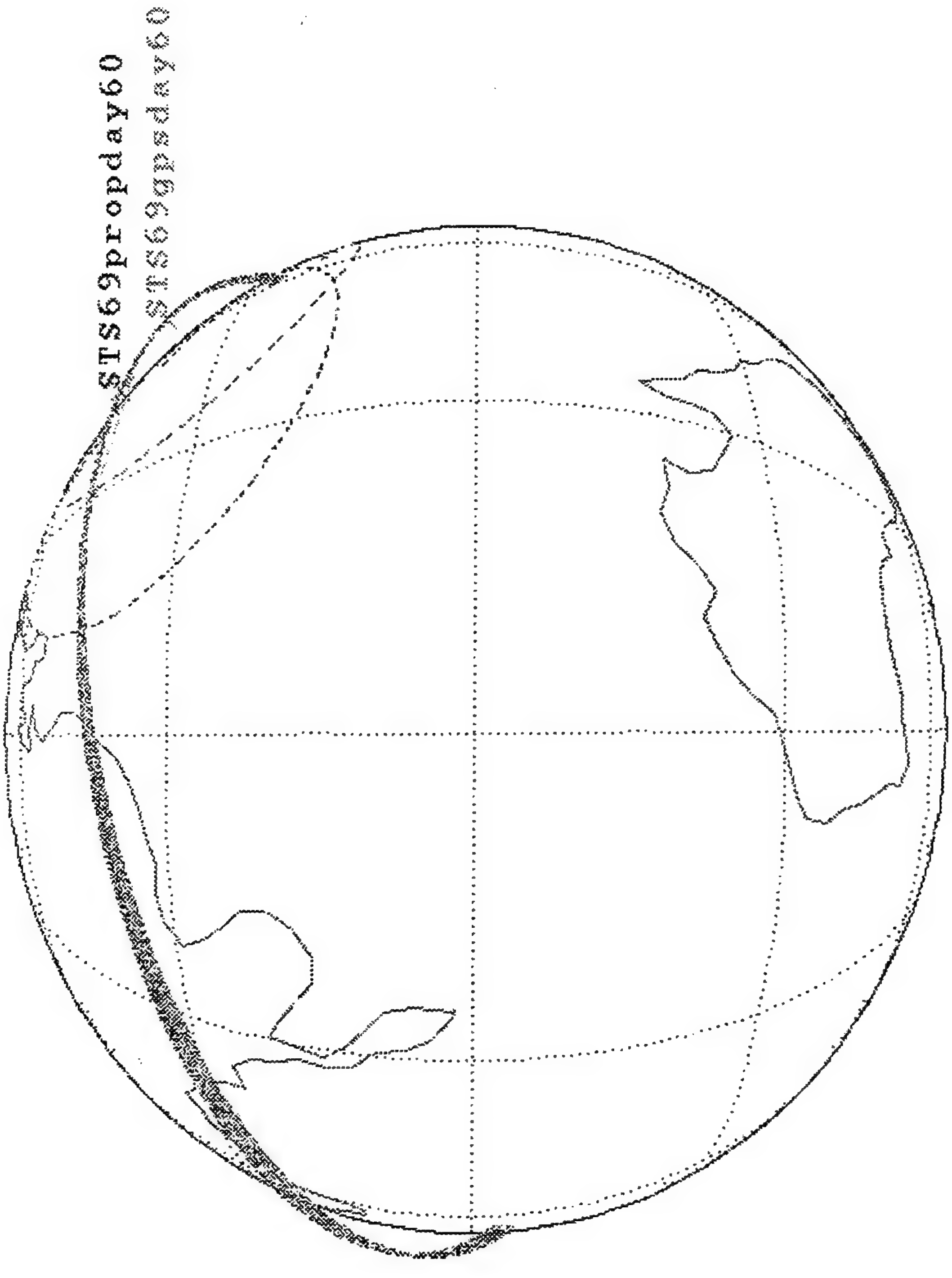
APPENDIX AB. DAY 260 STK PLOTS


80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160



STS60propday60
80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

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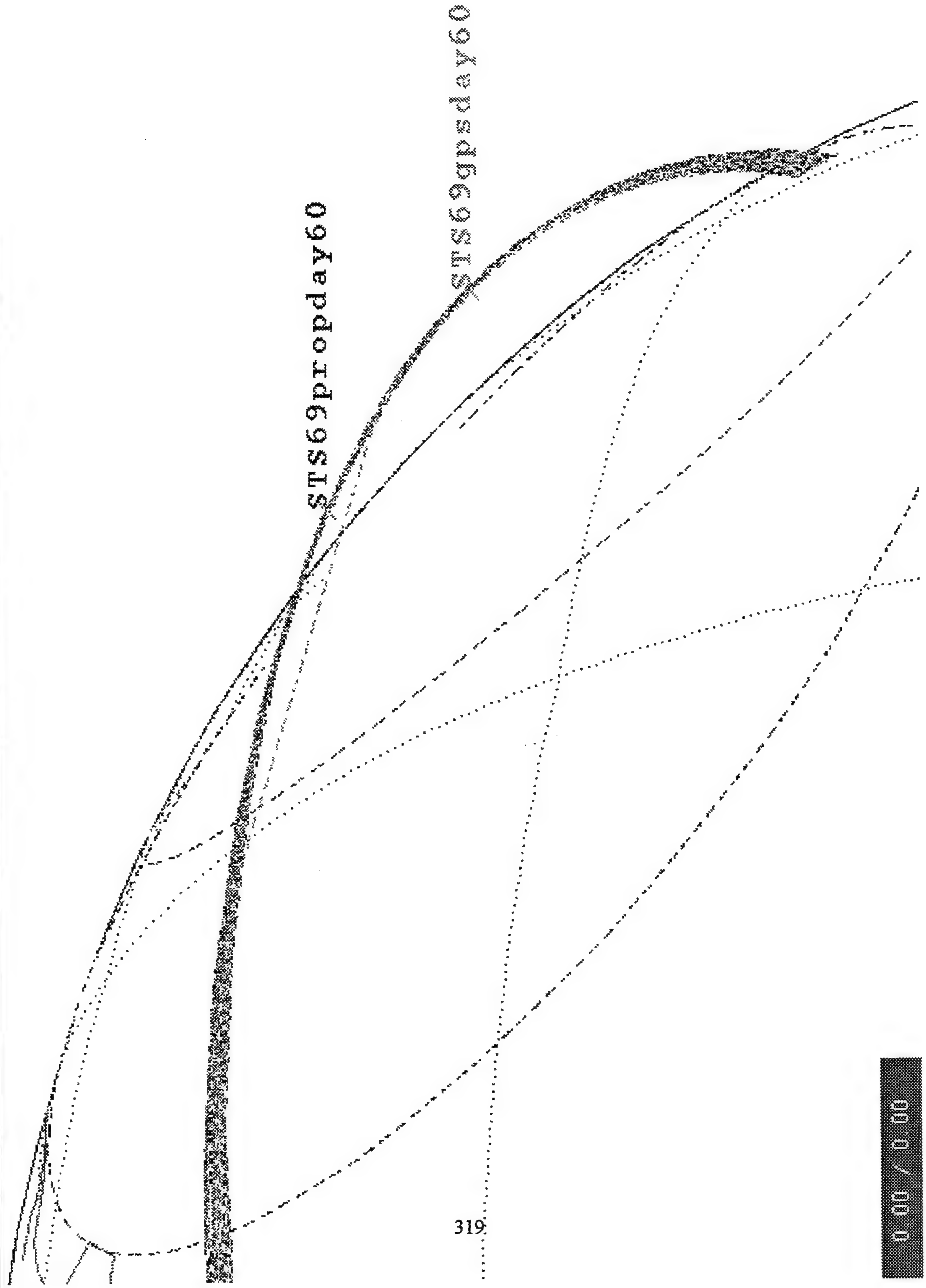
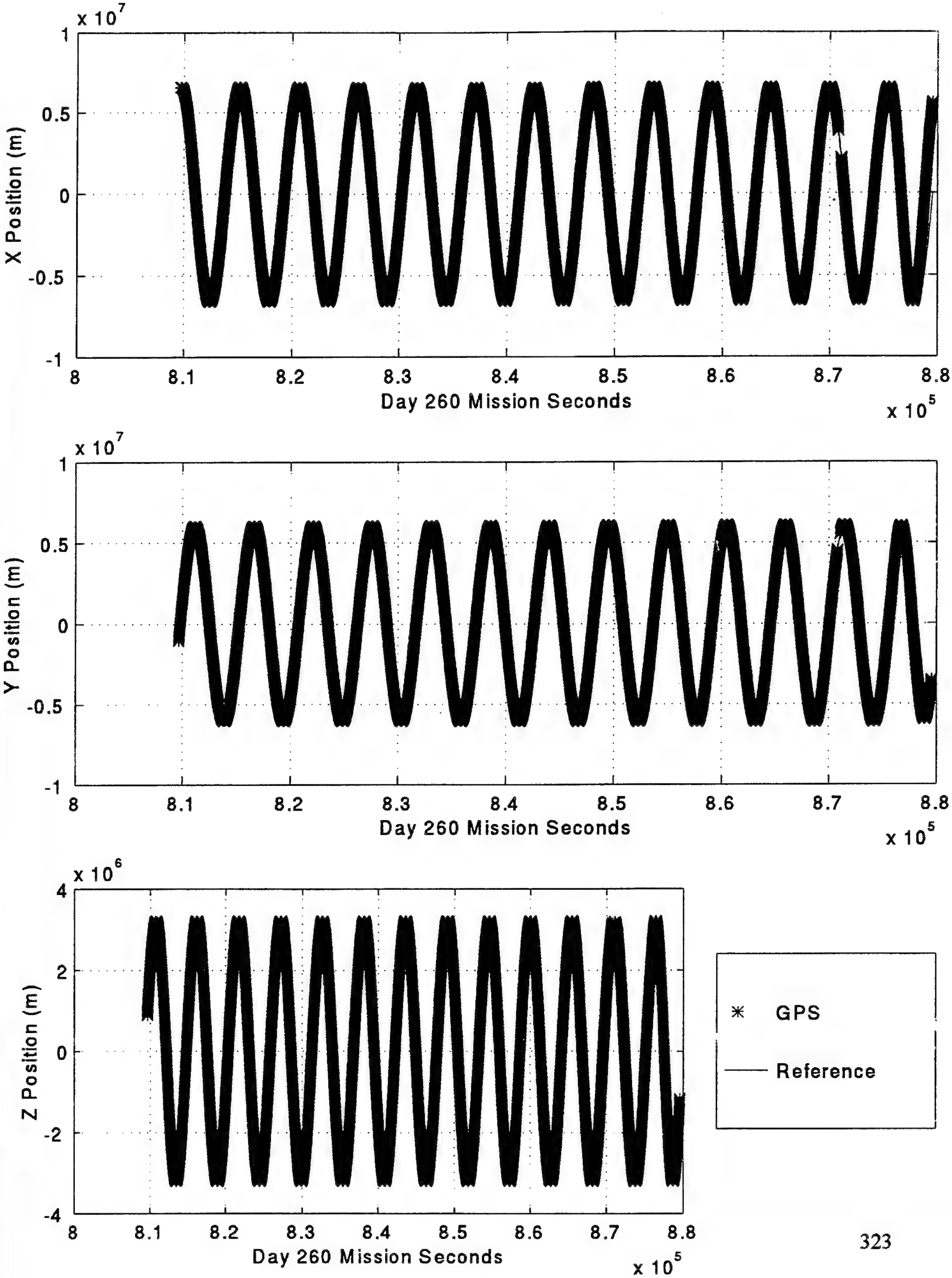
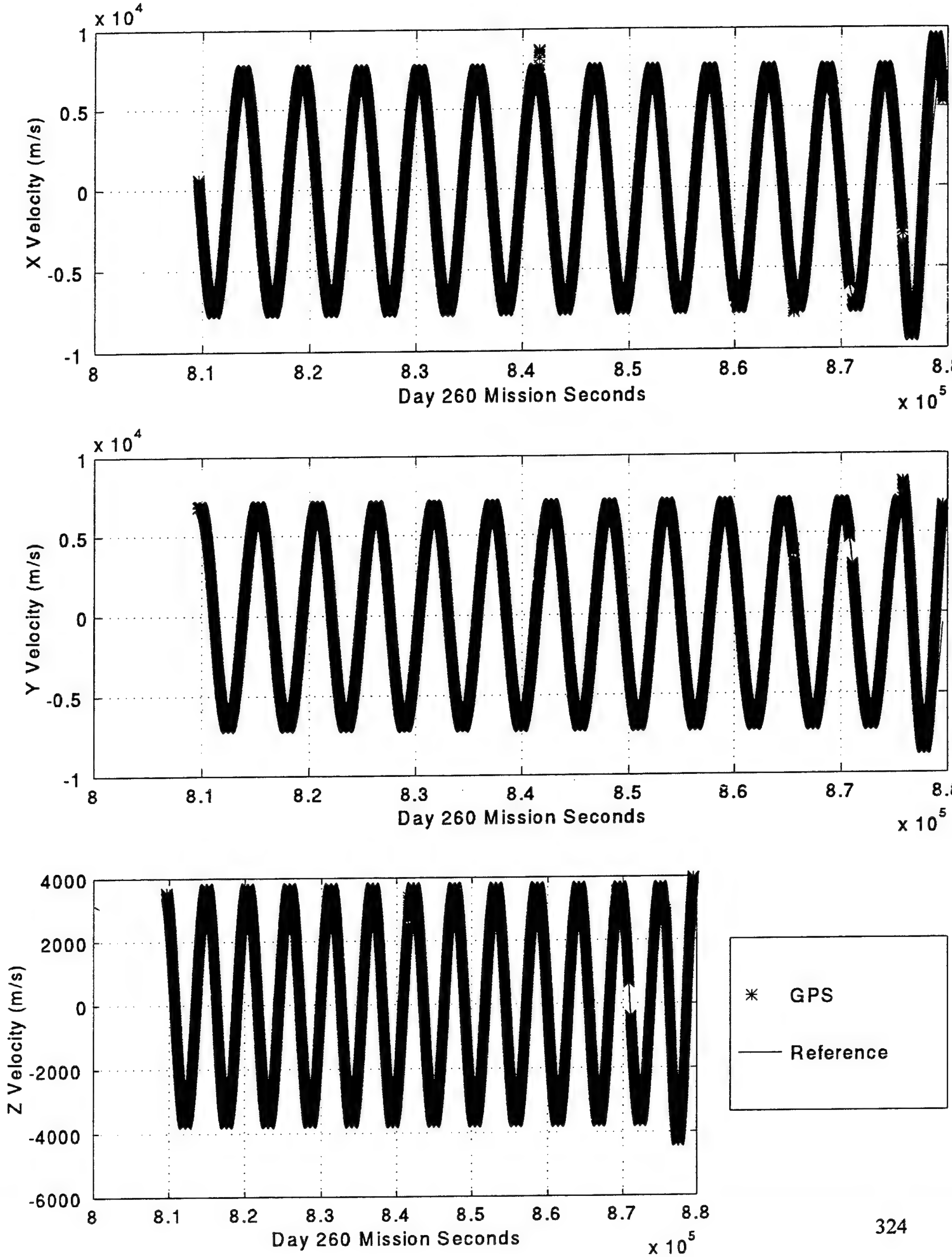
STS69gpsday60

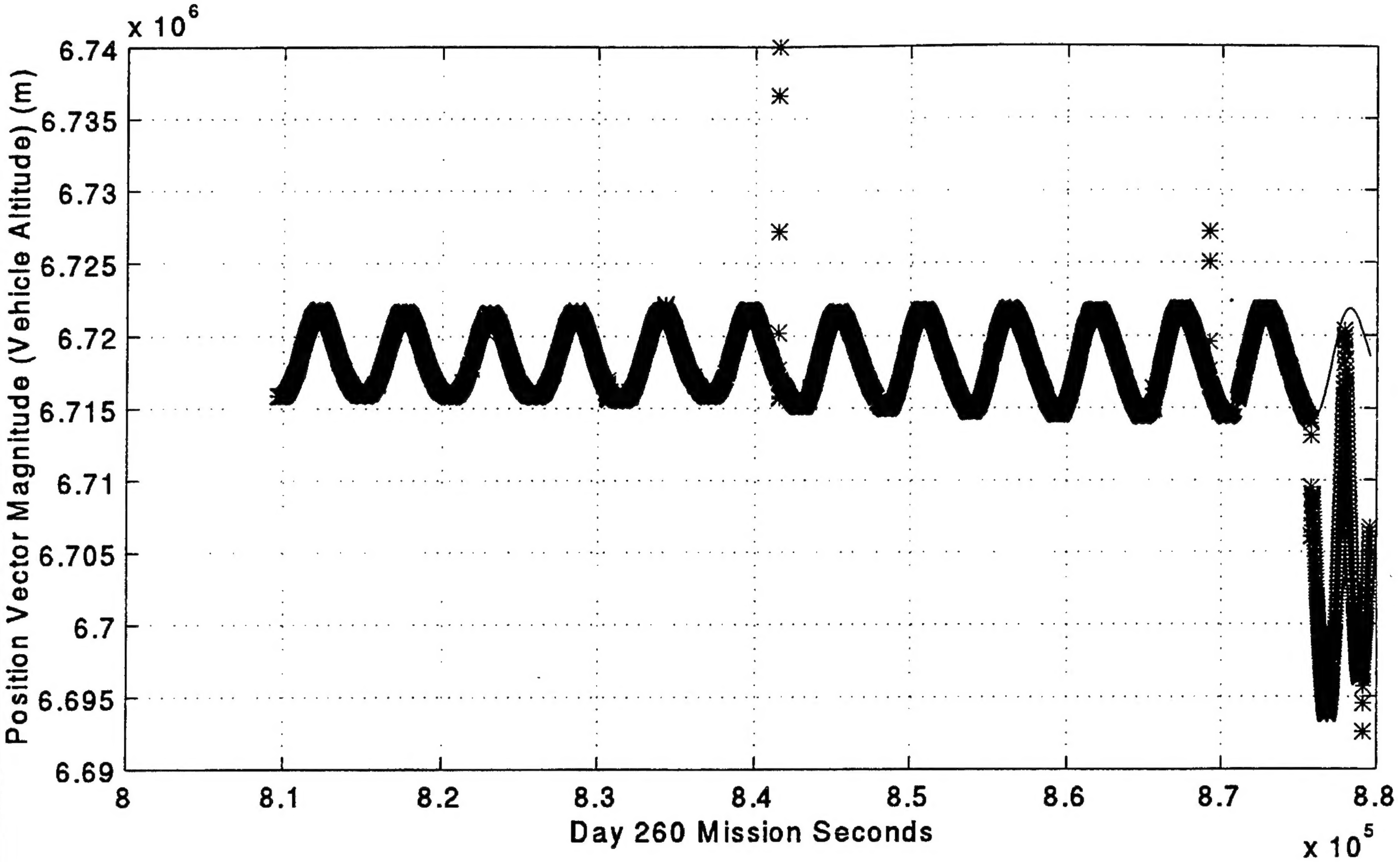

STS69propday60
STS69gpsday60
0.00 / 0.00

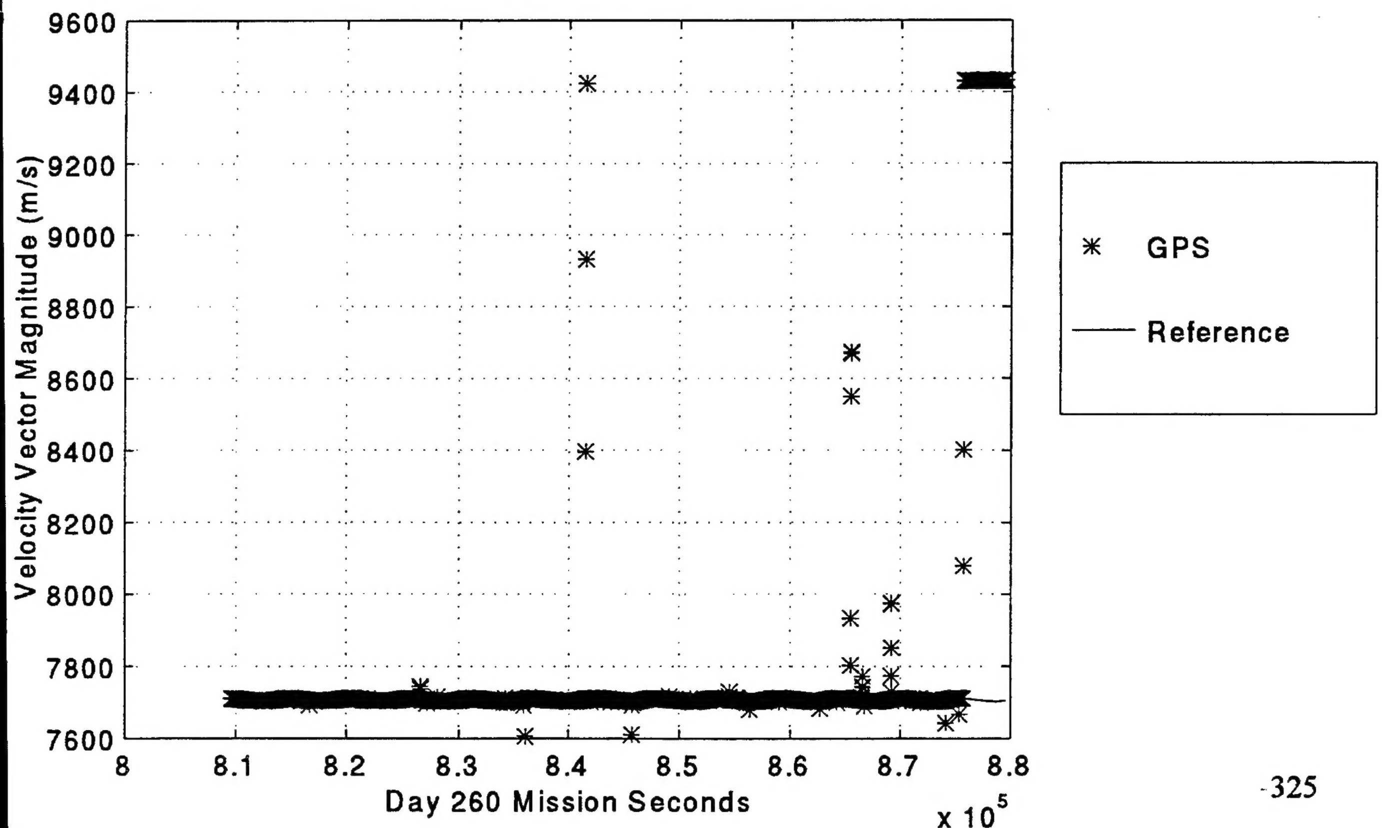
APPENDIX AC. DAY 260 MATLAB PLOTS



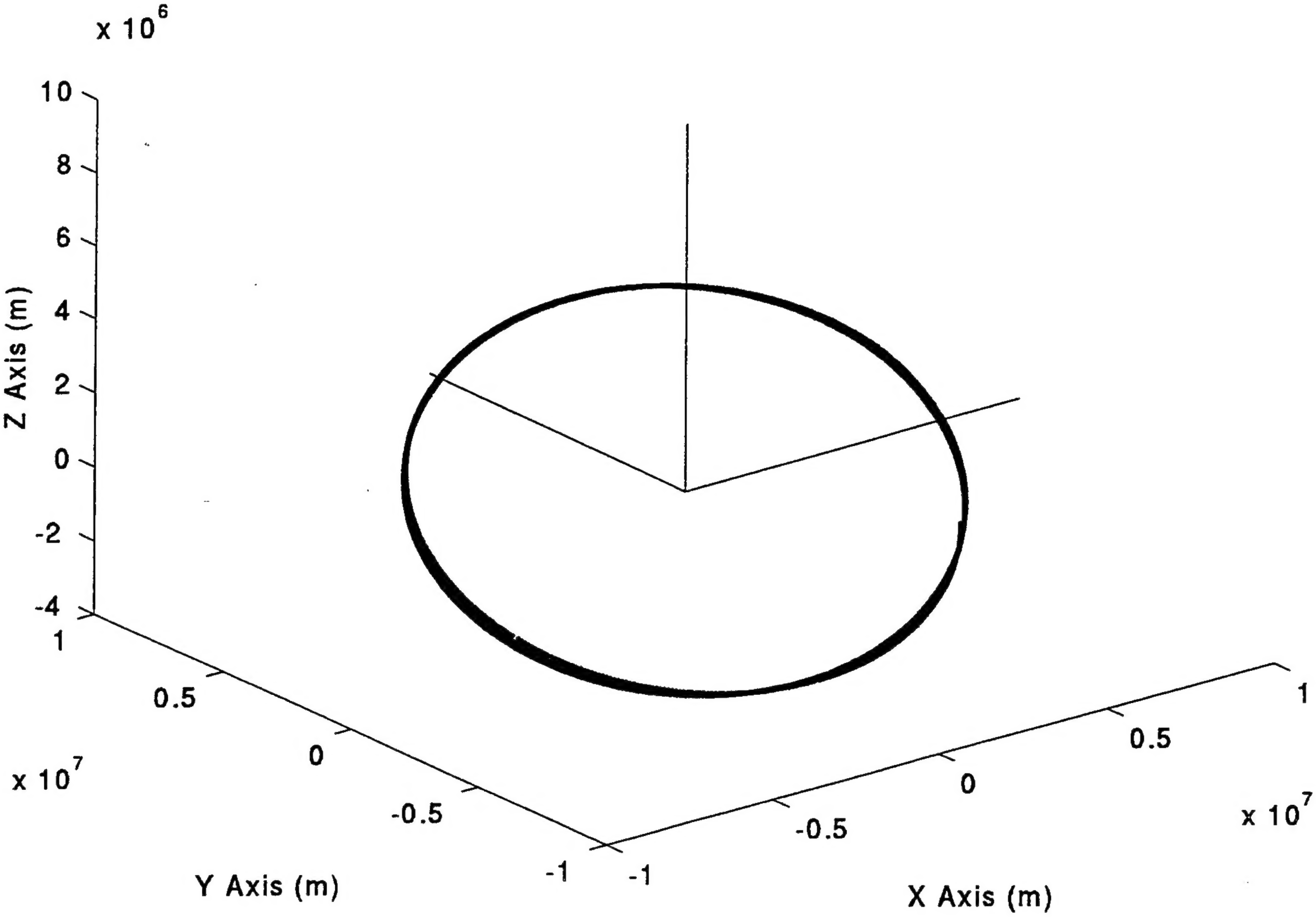
x 10^7
X Position (m)
1
0.5
0
-0.5
-1
8
8.1
8.2
8.3
8.4
8.5
8.6
8.7
8.8
Day 260 Mission Seconds
x 10^5
x 10^7
Y Position (m)
1
0.5
0
-0.5
-1
8
8.1
8.2
8.3
8.4
8.5
8.6
8.7
8.8
Day 260 Mission Seconds
x 10^5
x 10^6
Z Position (m)
4
2
0
-2
-4
8
8.1
8.2
8.3
8.4
8.5
8.6
8.7
8.8
Day 260 Mission Seconds
x 10^5
GPS
Reference


x 10^4
X Velocity (m/s)
1
0.5
0
-0.5
-1
8
8.1
8.2
8.3
8.4
8.5
8.6
8.7
8.8
Day 260 Mission Seconds
x 10^5
x 10^4
Y Velocity (m/s)
Day 260 Mission Seconds
x 10^5
Z Velocity (m/s)
4000
2000
0
-2000
-4000
-6000
Day 260 Mission Seconds
x 10^5
GPS
Reference


x 10^6
Position Vector Magnitude (Vehicle Altitude) (m)
6.74
6.735
6.73
6.725
6.72
6.715
6.71
6.705
6.7
6.695
6.69
8
8.1
8.2
8.3
8.4
8.5
8.6
8.7
8.8
Day 260 Mission Seconds
x 10^5


Velocity Vector Magnitude (m/s)
9600
9400
9200
9000
8800
8600
8400
8200
8000
7800
7600
8
8.1
8.2
8.3
8.4
8.5
8.6
8.7
8.8
Day 260 Mission Seconds
x 10^5
GPS
Reference

GPS Orbit for Day 260 in J2000 Coordinates



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